

IN-PLANT TESTING OF HIGH-EFFICIENCY HYDRAULIC SEPARATORS

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ABSTRACT

Hydraulic separators are commonly used for particle size classification and gravity concentration of minerals and coal. Unfortunately, the efficiency of these processes can be quite low due to poor equipment design and variations in feed consistency. To help alleviate these problems, an industry-driven R&D program has been undertaken to develop a new generation of hydraulic separators that are more efficient and less costly to operate and maintain. These units, which are commercially called the CrossFlow separator and HydroFloat separator, have the potential to improve performance (separation efficiency and throughput) and reduce operating costs (power consumption, water and reagent usage). In Phase I of this project, laboratory and pilot-scale test units were evaluated at various industrial sites in both the coal and mineral industries. Based on promising results obtained from Phase I, full-scale prototypes were purchased and installed by a major U.S. phosphate producer and a large eastern U.S. coal company. The test data obtained from these sites demonstrate that significant performance improvements can be realized through the application of these high-efficiency separators.

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1.0 INTRODUCTION

1.1 Hydraulic Separation

1.1.1 Classification Systems

Hydraulic separators are frequently used in the minerals processing industry to classify fine particle according to size and/or density. Although many devices have been developed over the years, a technique that has been gaining popularity in recent years is the teeter-bed separators. These devices, which are also commonly called hindered-bed or fluidized-bed separators, make use of differential particle settling rates to segregate particles according to size, shape, and/or density.

The tradition design of a hydraulic classifier consists of an open top vessel into which elutriation water is introduced through a series of distribution pipes evenly spaced across the base of the device. During operation, feed solids are injected into the upper section of the separator and are permitted to settle. The upward flow of elutriation water creates a fluidized bed of suspended particles within the separator. The small interstices within the bed create high interstitial liquid velocities that resist the penetration of the slow settling particles. As a result, small particles accumulate in the upper section of the separator and are eventually carried over the top of the device into a collection launder. Large particles, which settle at a rate faster than the upward current of rising water, eventually pass through the fluidized bed and are discharged out one or more restricted ports through the bottom of the separator.

It is obvious from the above description that quiescent flow conditions must exist within the separator to maintain a high efficiency. Excessive turbulence or changes in flow conditions can result in the unwanted misplacement of particles. Unfortunately, current hydraulic separators utilize a feed injection system that discharges directly into the main separation chamber. These

simplistic feed systems typically consist of a vertical pipe that terminates approximately one-third of the way into the main separator body. The pipe discharge is usually equipped with a dispersion plate to laterally deflect the feed slurry, but this approach creates turbulence within the separator that is detrimental to an efficient separation. In addition, the water that is injected with the feed solids must also report to the overflow launder. As a result, the rise velocity of the water is substantially increased at the feed injection point. Above the feed point, the liquid rise velocity is the sum of the elutriation water and the feed water flow rates. This discontinuity often results in a secondary interface of fluidized solids within the separator. In fact, at higher feed rates, the volume of water associated with the feed slurry is often greater than the volume of elutriation water; thus severely affecting the separation performance. Throughput capacities are also limited in conventional hydraulic separators due to the detrimental impact of feed water on unit performance.

Equipment maintenance is also important issue in the design of a hydraulic separator. Conventional teeter-bed designs use a series of lateral pipes located in the base of the separation zone. These pipes are perforated at regular intervals with large numbers of small diameter holes. Elutriation water is injected through these holes over the entire cross-section of the separator. The large water flow rates combined with the small injection hole diameters leave the device susceptible to frequent blockage/plugging due to contaminants in the process water. When several orifices become blocked, a dead zone occurs in the fluidization chamber resulting in a loss of performance in this area. As a result, conventional teeter-bed separators have an inherent design flaw that limits both the capacity and efficiency of the separator.

1.1.2 Concentration Systems

In addition to particle sizing applications, teeter-bed separators are also frequently used to separate various minerals based on differences in particle density. In this case, the coarse high-density particles settle against the rising flow of water and build a bed of teetering solids. This bed of high-density solids has an apparent density much higher than the elutriation water. Since particle settling velocity is driven by the density difference between the solid and liquid phase, the settling velocity of the particles is reduced by the increase in apparent density of the teetering bed. This artificial density forces low-density particles to report to the overflow of the separator and high-density particles to report to the underflow.

Some common examples of density-based teeter-bed applications include the separation of coal from rock, silica from iron ore, and silica from various heavy minerals (zircon and ilmenite). Unfortunately, the plant data indicate that efficient concentration can only be achieved if the particles are in the size range of 200 mesh to several millimeters and if the particle size ratio (top size to bottom size) is less than about four-to-one. In practice, coarse low-density particles will tend to gather at the surface of the teeter-bed interface because the elutriation water velocity is not sufficient to transport these large particles into the overflow launder. The large particles continue to gather at the bed interface until mass action forces them into the teeter bed, where they eventually misplaced into the high-density product. This inherent inefficiency can be partially corrected by increasing the elutriation water velocity to convey the coarser low-density solids into the overflow. Unfortunately, this approach is harmful to the concentrate grade since it also causes the finer high-density solids to be misplaced into the overflow launder. Because of these shortcomings, the separation efficiency obtained using teeter-bed separators is often poor in industrial operations. In most cases, the valuable component (i.e., coal, iron ore, ilmenite and

zircon) frequently must be reprocessed in “polishing” circuits to achieve the desired product quality. The problem is that conventional teeter-bed separators are inherently inefficient when used to treat mineral assemblages that have either a wide particle size distribution or a narrow density distribution.

1.3 Literature Review

1.3.1 Hydraulic Classifier Types

There are three main characteristics that distinguish a hydraulic classifier from other classifiers. First, discharge of the oversize material from the device depends upon its gravitational flow properties and not mechanical means such as a screw or rake. Coarse particles settle at a rate faster than the upward current of the elutriation water, and exit the unit through a valve or spigot at the base of the unit. The second distinctive characteristic of a hydraulic classifier is the unit is not fed under pressure; the primary source of classification is based on differential particle settling rates to segregate particles according to shape, size, and/or density. Finally, hydraulic classifiers utilize at least one, and sometimes both, of the following two mechanisms (NC State, 1992):

- (i) *Hindered Settling* - An oversized particle settles against upward flowing fluid; the greater the density of the fluid, the larger the particle that will remain suspended (or teetered) in the fluid. Hindered settling is a function of particle size, density and concentration, liquid density and viscosity as well as the charge density.
- (ii) *Elutriation* - An undersize particle is lifted by an upward flowing stream of water; the greater the upward velocity, the larger the particle that will be lifted.

When the feed size distribution is within acceptable limits, hydraulic classifiers can also be used for the concentration of particles based on differences in density. Over the years, various units have been developed and can be primarily categorized by the method in which the coarse material is discharged from the separation zone of the unit (Heiskanen, 1993). The two main operational categories are: (i) classifiers that operate with free and/or hindered settling that have virtually no control of the underflow (or coarse fraction) discharge and (ii) classifiers that do attempt to control the underflow discharge causing the formation of a teeter bed. Classifiers that do not attempt to control the underflow discharge can be further subdivided into mechanical and non-mechanical categories.

1.3.2 *Mechanical Hydraulic Classifiers*

The *Hukki Cone Classifier* is a mechanical classifier invented by R.T. Hukki in 1967 and consists of a cylindrical tank where feed is introduced into the tank on a slowly rotating distribution disk, which causes a slight centrifugal action to it. The bottom of the tank is conical shape where water sprays are used as elutriation water. Coarse material is discharged through a pinch valve in the bottom of the cone. The key to this unit is in the conical section; where a ring of vertical, radial vanes are located to allow the pulp to rise upwards in a laminar fashion. The unit was originally designed to treat low quality sands, but is not used in practice today.

The *Sogreah Lavodune Classifier* is another mechanical classifier that consists of a cylindrical tank and a cone. Lower density counter-current classification is enhanced by laminar flow in this unit. A downcomer introduces feed material into the unit approximately one third of the distance from the top of the unit. The volume of the unit is restricted in the cone section where classification takes place in high suspension densities. The fine material rises and is

discharged over the overflow lip of the unit. A plunger in the base of the unit is used to regulate the discharge rate through the bottom of the unit. As with the Hukki cone, this unit is not used in industry today.

1.3.3 Non-Mechanical Hydraulic Classifiers

Linatex classifiers have been in the industry for several years in a variety of applications. The *Linatex S Classifier* is the company's version of a non-mechanical dense flow hydraulic classifier. The pulp is fed by a downcomer into the column where it comes in contact with a deflector plate that causes the flow to turn radially outwards and upwards. The ratio of water between underflow and feed streams controls the upward current at the deflector plate and thus the cut size (Heiskanen, 1993). The unit is very inefficient for sharp separations as it inherently bypasses a large volume of material. It is best utilized for slimes removal.

The Krebs C-H Whirlsizer is another type of non-mechanical dense flow hydraulic classifier. It uses a controlled water addition to a gently swirling pulp to clean the coarse fraction from fines (Heiskanen, 1993). The upper part of the unit is cylindrical in shape, with the lower unit forming a cone as in many of the other units described thus far. The lowermost section of the cylinder contains an internal cone that forces coarse particles into the narrow gap between the wall and the cone. Elutriation water is added below this from small holes, moving the pulp in a swirling action. While no teeter bed is formed, classification takes place by means of hindered settling, allowing the coarse material to settle past the internal cone and the fines to overflow through the top of the unit. It is designed for sand classification and targets the non-spherical materials such as vermiculite, mica and kyanite (Heiskanen, 1993).

1.3.4 Fluidized Bed Hydraulic Classifiers

The traditional design of a fluidized bed hydraulic classifier consists of an open top vessel into which elutriation water is introduced through a series of distribution pipes evenly spaced across the base of the device. During operation, feed solids are injected into the upper section of the separator and are permitted to settle. The elutriation fluid in a fluidized bed supports the weight of the particles within the bed by flowing between the particles. The small interstices within the bed create high interstitial liquid velocities that resist the penetration of the slow settling particles. As a result, small particles accumulate in the upper section of the separator and are eventually carried over the top of the device into a collection launder. Large particles, which settle at a rate faster than the upward current of rising water, eventually pass through the fluidized bed and are discharged out one or more restricted ports through the bottom of the separator.

One of the first hydraulic classifiers to utilize a teeter bed was the Stokes unit which was developed to sort the feed to gravity concentrators. Each teeter chamber is provided at its bottom with a supply of water under constant head which is used for maintaining a teetering condition in the solids that find their way down against the interstitial rising flow of water (Wills, 1992). Each chamber is fitted with its own pressure sensor that monitors the conditions in the chamber and automatically adjusts the discharge to maintain a balanced pressure caused by the teeter bed. A valve at the base of each compartment can be hydraulically or electrically operated to adjust the height of the teeter-bed. As the bed level increases, the pressure will also increase and the valve will open. Likewise, as the bed lowers, the pressure decreases and the valve will close. This action maintains a constant level and, therefore, constant density within the separator.

A more recent hydraulic classifier utilizing the teeter bed is the *Linatex Hydrosizer*. The Linatex Hydrosizer is a non-mechanical, hindered-settling classifier that maintains a fluidized teeter bed, but does not have the same elutriation water distribution or feed distribution as the CrossFlow separator. The pulp is fed into a central feed column where it comes in contact with a deflector plate that causes the flow to turn radially outwards and upwards. Extensive testing of a pilot-scale unit at a North Carolina phosphate plant was conducted in the early 1990's to attrition scrub and deslime flotation feed with promising results. Additional testing has been conducted at other mineral industries including mineral sands and aggregates. The Linatex Hydrosizer was marketed for sizing applications ranging from 28 mesh to 100 mesh, with some preliminary testing on finer material (NC State, 1992).

Phoenix Process Equipment has developed another type of fluidized bed hydraulic classifier called the Hydrosort. This separator and classifier is currently utilized in the aggregate industry, as well as some others, for separating light, harmful contaminants, such as lignite and wood, in sand washing, and for fractional sand classifications (Phoenix Process Equipment, 2003). The Hydrosort incorporates a fluidized bed created by an upward current of water flow to classify product or separate impurities in the same fashion as the Linatex Hydrosizer. A feature emphasized by Phoenix Equipment is the clog-free classifier bottom, which distributes the upward water flow equally over the separating area. Unlike in the CrossFlow where feed enters the unit tangentially, both the Phoenix Hydrosort and the Linatex Hydrosizer have a feed distribution pipe that enters the top of the unit and discharges feed into the separation chamber.

The Floatex fluidized-bed classifier (or Floatex Density Separator) is the most recent hydraulic separator designed. Like the other units, this separator utilizes a teeter bed which is formed by solids settling against an upward current of elutriation water. Coarse material settles

through the teeter-bed, while finer particles report to the overflow of the unit. A differential pressure cell and discharge valve controls the bed level in the unit. This efficient unit sees very little fines bypassed to the underflow and as a result, the unit produces a relatively clean underflow.

1.3.5 Hindered Settling

Hindered settling is an important phenomenon in all of the aforementioned hydraulic classifiers. Hindered settling considers the interaction of other particles in classification systems either on a particle-particle level or from the behavior of the particle assemblies. The interactions between two particles may be due to particles settling close to each other or to the wake effect of a larger particle on the settling of a smaller particle (Heiskanen, 1993). According to Littler (1986), the hindered settling phenomenon begins to take place at approximately 20% solids by mass. The cohesive force between two particles settling very close to one another is great enough for the particles to fall together and be treated as a single particle of greater size and lower density. A wake effect is caused when a larger particle captures a smaller particle in its wake as it is settling and as a result, the smaller particle falls at a velocity much higher than its free settling velocity. In a teeter bed, however, the high solids concentration increases the likelihood of particle collision, and these particles lose some of their settling velocity in these collisions. The fine particles, therefore, have a higher likelihood of being driven to the overflow launder by the upward current of elutriation water. And as a result, hindered settling is more efficient than free settling classification due to the decrease in fines entrained in the underflow.

An analysis of the behavior of particle assemblies can be categorized into two parts. Particle assemblies settling may occupy the whole fluid or they may be considered as clusters of

particles which only fill a fractional volume of the fluid (Heiskanen, 1993). When the assemblies occupy the entire fluid they may be treated as a uniform pulp where the interactions are between the individual particles. As clusters, the particles are analyzed as large particles of reduced density and rigidity. The probability of this occurring increases with narrower particle size ranges, and is magnified in gravitational classification where high solids contents are present.

From an analysis standpoint, hydraulic classifiers are characterized by two factors: (i) the size separation and (ii) the sharpness of the separation. For theoretical analyses it is convenient to define separation size as that of particles which settle just fast enough *on the average*, to be totally collected in the underflow (Weiss, 1985). Slight variations in settling rates will occur between particles of the same size and density due to differences in shape and turbulence in the separator. The sharpness of the separation defines how the particles segregate into the product and the tails streams. Under ideal conditions, a classifier should partition particles coarser than the cut size d_{50} into the coarse stream and finer particles into the overflow (Heiskanen, 1993). The efficiency of this cut is based on the amount of misplaced particles in both streams.

1.4 High-Efficiency Hydraulic Separators

In order to further promote the use of hydraulic separators, a new generation of teeter-bed technologies known as the “CrossFlow Separator” and “HydroFloat Concentrator” has been developed by Eriez Manufacturing in conjunction with research universities and mineral producers. These new high-efficiency separators incorporate novel design features to improve performance (separation efficiency and throughput) and reduce operating costs (power consumption, water usage and reagent dosage). Both of these innovative technologies are high-tech variations of the conventional teeter bed separator concept. As such, these high-efficiency

units can be readily adopted by industry once the operational knowledge base has been fully developed and the merits have been demonstrated in an industrial environment.

1.4.1 CrossFlow Separator

Figure 1.1 shows schematic of the CrossFlow Separator. Compared to a conventional hydraulic classifier, the CrossFlow design uses an improved feed delivery system that gently introduces the feed slurry across the top of the separator as opposed to injecting the slurry at a high velocity directly into the teeter-bed. As previously stated, high slurry feed volumes create turbulent mixing that has a detrimental impact on separator performance. In the new feed delivery system, the feed velocity is reduced using a transition box. The purpose of this box is two-fold. First, the feed transition box increases the flow area to the full width of the separator so that the slurry velocity, and any associated turbulence, is minimized. The second unique feature

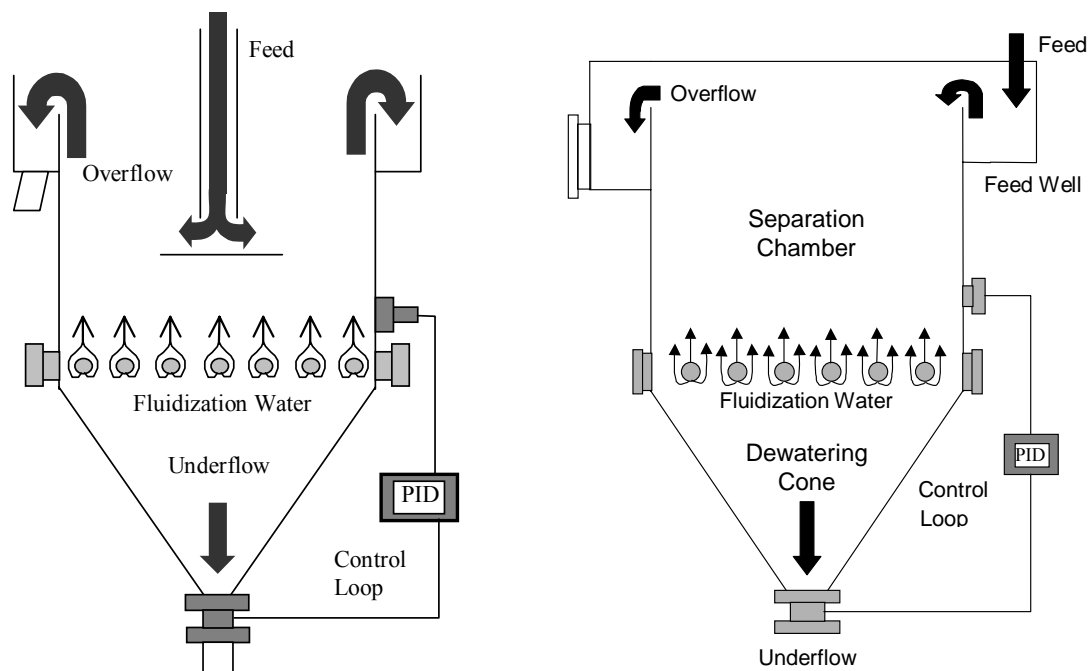


Figure 1.1. Comparison of traditional teeter-bed (left) with CrossFlow (right) classifiers.

is its ability to tangentially feed the separator. This stilling-well, which is located at the top of the separator, smoothly passes the feed slurry horizontally across the top of the cell. Compared to conventional systems, the feed introduction system ensures that variations in feed slurry characteristics (e.g., solids content) do not impact separator performance. In the CrossFlow, the teeter-water velocity remains constant throughout the separation chamber at all times, while the velocity in a conventional classifier generally increases above the feed addition point (Figure 1.2). A duct plate is also located at the discharge end of the feed introducer to prevent short-circuiting of solids directly to the overflow launder.

Another design feature incorporated into CrossFlow classifier is the improved water

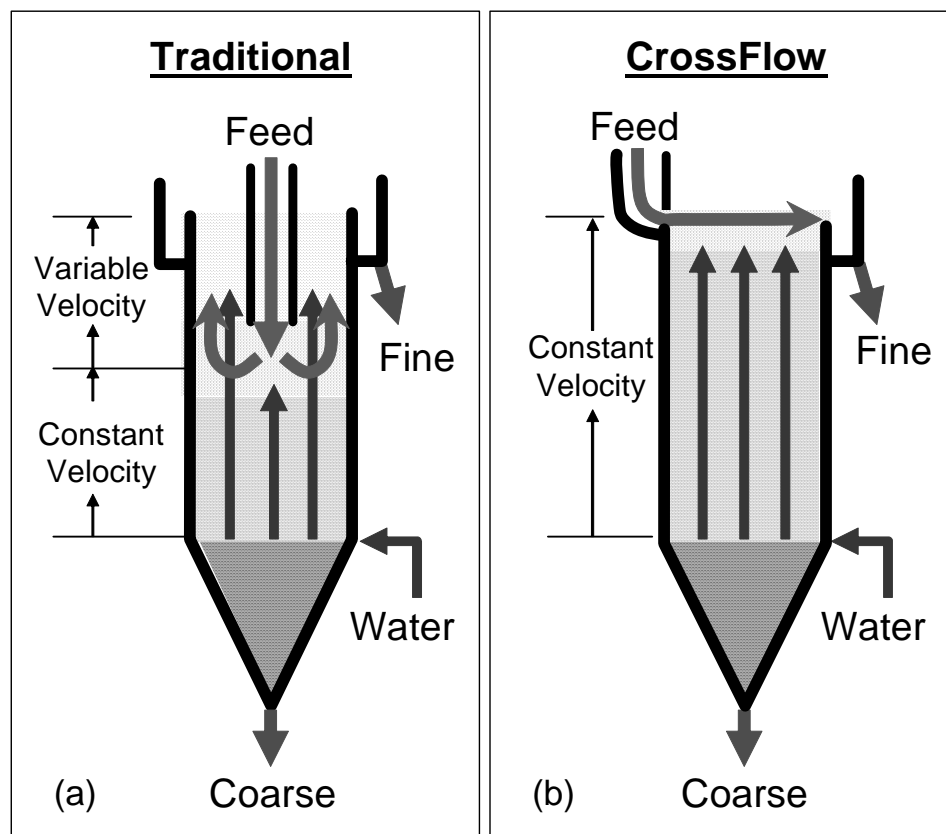


Figure 1.2. Comparison of water flow velocities in different classifiers.

distribution system. A novel approach has been developed that incorporates a baffle plate to disperse the elutriation water across the base of the separator. In this design, a horizontal slotted plate is located at the base of the separation chamber. Water is introduced beneath the plate through a series of large diameter holes (>1.25 cm). However, unlike existing separators, these orifices are located at distant intervals (typically >15 cm) and serve simply to introduce the water, while water dispersion is achieved by the baffle plate. This modification essentially eliminates problems associated with distributor pipe plugging. The combined use of the improved feed injection system and simplified water distribution system makes it possible to increase both the separation efficiency and throughput capacity while eliminating mechanical problems associated with traditional designs. Because of the higher throughput capacity, the operating demands in terms of power, water consumption and maintenance are lower for the CrossFlow when reported on a per ton of concentrate basis.

1.4.2 HydroFloat Separator

It is generally accepted that teeter bed technologies, such as the CrossFlow design, can only be applied to mineral systems that have (i) a relatively narrow particle size distribution and (ii) a moderately large difference in particle densities. To overcome these limitations, technical personnel at Eriez Manufacturing have been working with industry to develop a novel air assisted hydraulic concentrator called the HydroFloat separator. This innovative process, which is shown in Figure 1.3, combines the flexibility of a flotation process with the high capacity of a density separator.

During operation, particles in the feed stream are treated with a reagent (called a collector) so that the surface of one or more of the mineral particles is made hydrophobic. The

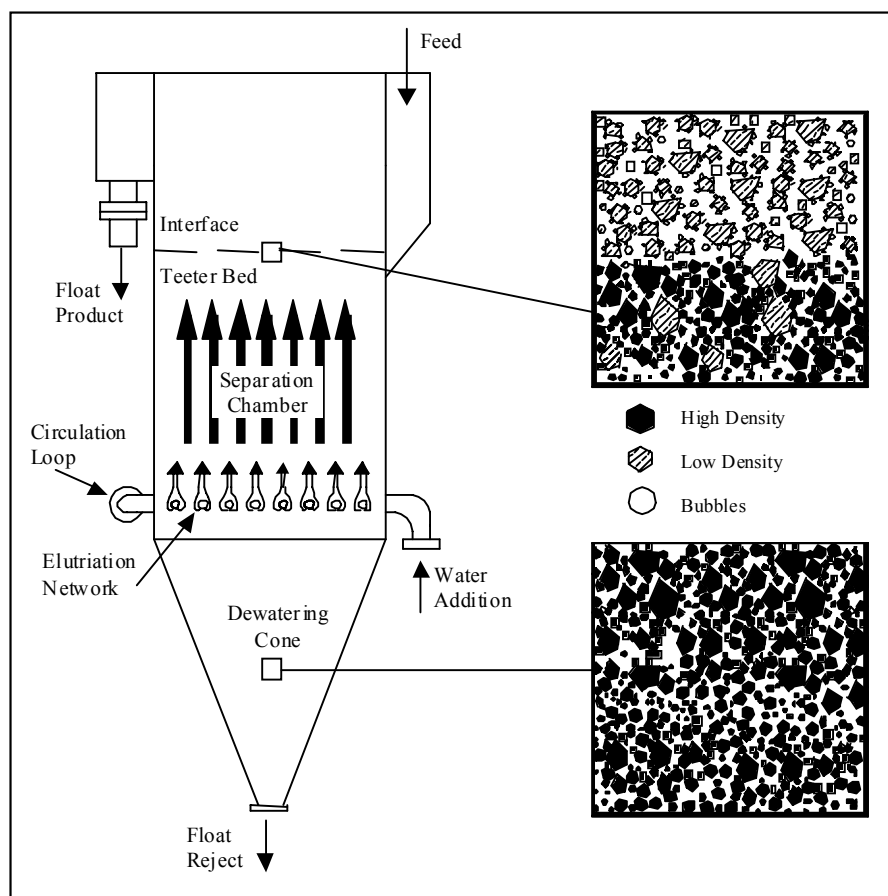


Figure 1.3. Schematic drawing of the HydroFloat separator.

reagentized feed slurry is then introduced into the top of the separator where the feed particles are allowed to settle into the teeter bed at a rate dictated by their size and density. The teeter bed is continuously aerated by injecting compressed gas and a small amount of frothing agent into the fluidization water. The gas is dispersed into small air bubbles by circulating the water through a high-shear mixer in closed-loop with a centrifugal pump. Because of differences in wettability, the air bubbles in the fluidization water become selectively attached to hydrophobic particles within the teeter bed, thereby reducing their effective density. The lighter bubble-particle aggregates rise to the top of the denser teeter bed and are collected as overflow from the top of the separation chamber. In contrast, air bubbles do not become attached to hydrophilic

particles. These particles continue to move down through the teeter bed and are eventually discharged as a high solids stream (e.g., 75% solids) through a control valve at the bottom of the separator.

The HydroFloat separator makes it possible to apply density separation technology to nearly any mineral system, even if the natural densities of the valuable component and gangue are the same. In this case, the surface wettability of different particle species can selectively modified to create lighter bubble-particle aggregates that can be separated from unwanted gangue particles. For some systems, such as coal, the valuable particles are naturally hydrophobic and will spontaneously attach to air bubbles, while associated mineral contaminants are hydrophilic and will not attach. Other systems, such as iron ore with a silica contaminant, require chemical activation of the silica to promote bubble-particle attachment. The method for chemical activation using reagents known as collectors is well known and is routinely used for the selective recovery of fine particles (less than 0.2-0.3 mm) using froth flotation processes.

The HydroFloat separator has several potential advantages compared to conventional froth flotation cells. The use of a fluidized bed significantly improves the recovery of coarse particles by reducing turbulence, enhancing buoyancy, increasing particle retention time, and improving bubble-particle contacting. In addition, the new technology significantly reduces energy consumption since no mechanical agitator is required. The system is also capable of lowering capital and installation costs since less total cell volume is required per unit of throughput capacity due to the high solids content within the teeter bed.

The unique design features of the HydroFloat separator make it ideally suited for recovering very coarse particles that are too large to be upgraded by existing froth flotation processes. This capability is very important to several industries (potash, phosphate, coal, etc.)

that commonly have difficulties in recovering the coarser particles in the feeds to the plant flotation circuits. One reason for the improved recovery of coarse particles is the upward flow of elutriation water that helps to lift the larger particles into the product launder. The high content of solids and quiescent flow conditions within the teeter bed separator also serve as an ideal environment for collision and adhesion of air bubbles and particles. In addition, the high solids content within the teeter bed separator makes it possible to treat large tonnages in a very compact volume as compared to conventional flotation separations which are conducted at very low solids contents using large volume cells. Also, substantial energy savings are possible since the countercurrent flow of feed particles and elutriation water eliminates the need for intense agitation normally required in conventional flotation machines.

1.5 Project Objectives

The primary objective of this project is to demonstrate the enhanced capabilities of novel high-efficiency hydraulic separators for particle classification and concentration in the mineral and coal industries. Preliminary studies suggest that these technologies offer better separation efficiency (e.g., higher recovery, improved grade, and increased capacity) and lower operating cost (e.g., lower consumption of electrical power, process water, and chemical reagents) than conventional processes that are currently used for mineral and coal beneficiation. To meet this objective, a two-phase test program was conducted at several industrial plant sites.

The objective of the Phase I effort was to systematically establish the effects of key design and operating variables on the performance capabilities of these high-efficiency separators. This effort involved extensive field tests conducted using small pilot-scale units at several different mineral processing and coal preparation plants. The pilot-scale tests were

necessary to collect data that would be impractical or cost prohibitive to gather in full-scale tests for single industrial sites.

The objective of the Phase II effort was to further refine and demonstrate the effectiveness of the novel separation technologies by designing, installing and evaluating prototype proof-of-concept (POC) separators at commercial sites. This work was required (i) to accurately define the performance capabilities of these high-efficiency processes in an industrial environment, (ii) to provide critical scale-up criteria for the design of larger production units, and (iii) to fully demonstrate the potential economic benefits realized via the implementation of these innovative technologies.

2.0 EXPERIMENTAL

2.1 General Approach

To achieve the stated project objectives, a cooperative R&D program was conducted that involved two major research universities (Virginia Tech and University of Kentucky), a leading manufacturer of process equipment (Eriez Manufacturing, Inc.), and several mineral processing and coal preparation operations (Mosaic Company, TECO Mining and KenAmerica Coal). Virginia Tech, which served as the prime contractor for the effort, provided day-to-day coordination of project activities and was responsible for the set-up, operation, sampling, and evaluation of the proposed test circuits. Personnel from Eriez and the University of Kentucky assisted Virginia Tech in this effort by providing on-site personnel during the field installation and testing programs. These organizations were assisted by personnel from the participating industrial companies who provided critically needed expertise related to the operation of their plants. Engineering personnel from these companies also played an active role in the on-site coordination of the fieldwork, assisted in the analysis, review, and interpretation of the test data, and provided a variety of on-site services such as mechanical/electrical services, sample preparation, and sample analysis.

For management reasons, the project work was performed in two distinct phases encompassing twelve individual tasks (see Table 2.1). In Phase I, continuous pilot-scale test circuits were set up and tested at several industrial sites. For phosphate operations, the pilot-scale tests focused primarily on improving the performance of mineral flotation circuits using the HydroFloat separator. Experimental studies were, however, also conducted at this site to evaluate the ability of the CrossFlow classifier to simplify plant circuitry and reduce operating costs (i.e., power, water and reagent costs). For the coal operations, the pilot-scale test work was conducted

Table 2.1. Listing of project tasks conducted in Phase I and II.

Phase I – Pilot-Scale Testing	Phase II – Prototype Testing
Task 1 - Phase I Project Planning	Task 6 - Phase II Project Planning
Task 2 - Field Testing	Task 7 - Scale-Up Design/Engineering
Subtask 2.1 - Equipment Setup	Subtask 7.1 - Flowsheet Design
Subtask 2.2 - Shakedown Testing	Subtask 7.2 - Equipment Design
Subtask 2.3 - Detailed Testing	Task 8 - Fabrication/Commissioning
Task 3 - Process Evaluation	Task 9 - Performance Testing
Task 4 - Phase I Sample Analysis	Task 10 - Detailed Evaluation
Task 5 - Phase I Project Report	Task 11 - Final Project Report

using the high-efficiency CrossFlow unit to improve the recovery and quality of saleable products from their fine coal processing circuits. The Phase I activities required approximately 18 months of work for project planning, field testing, process evaluation, sample analysis and reporting. Research personnel from the participating universities, equipment manufacturer, and mining companies jointly conducted these activities.

After successfully completing Phase I activities, suitable industrial locations were identified for the installation of production-scale prototypes of both the HydroFloat and CrossFlow technologies. Approximately 18 months of additional work was required in Phase II for additional project planning, scale-up design/engineering, fabrication and commissioning, performance testing, detailed evaluation and reporting. The equipment manufacturer and two industrial participants (one mineral and one coal) were largely responsible for the completion of these on-site demonstrations.

2.2 Project Tasks for Phase I - Pilot-Scale Testing

Task 1 – Phase I Project Planning

Prior to initiation of experimental work, a Detailed Project Work Plan was prepared and submitted to DOE for approval. The work plan provided a detailed description of the proposed

test program, experimental procedures, analytical methods, and reporting guidelines for the implementation and completion of the proposed Phase I and Phase II efforts.

Task 2 – Field Testing

The Phase I field-testing involved (i) equipment setup, (ii) shakedown testing, and (iii) detailed testing of pilot-scale separators. Subtask 2.1 (Equipment Setup) focused on the transportation and installation of pilot-scale test units for each industrial site. For mineral operations, it was also necessary to install conditioning tanks in order to fully evaluate the circuit configurations. In addition, a wide variety of ancillary equipment, such as pumps, sumps, meters, etc., were also installed at each test site. Personnel from Eriez Manufacturing and the participating universities coordinated this effort in conjunction with staff from the participating mining companies. Subtask 2.2 (Shakedown Testing) was then initiated to resolve any unexpected operational problems that occurred at each site and to confirm that pumping capacities, pipe sizes, electrical supplies, control systems, etc., were adequate. Personnel from the participating universities and Eriez Manufacturing were largely responsible for the completion of this subtask. Finally, in Subtask 2.3 (Detailed Testing), several series of detailed tests were conducted using the pilot-scale test units to investigate the effects of the key operating and design parameters on separator performance. Important design parameters included (i) feed injection depth, (ii) distributor design, (iii) and baffle configuration. Key operating variables included (i) fluidization water rate, (ii) solids mass feed rate, (iii) volumetric slurry feed rate, (iv) teeter bed depth, and (v) reagent dosage (when required). When appropriate, sampling campaigns were also conducted at each of the industrial site to establish the baseline performance of the existing plant equipment so that the data could be fairly compared with that

obtained from the high-efficiency hydraulic separators. The responsibility for completing this work was jointly shared between the university personnel and technical staff from the mineral and coal producers.

Task 3 – Process Evaluation

This task involved the compiling and archiving of the raw test data. In most cases, data analysis consisted of evaluating the individual and combined capabilities of the various processing circuits examined at the industrial sites. This subtask ran concurrently with the test work conducted in Task 2 at each of the industrial test sites. Items addressed in the evaluation included (i) a summary of all the major experimental data, engineering analyses, computations, and test results; (ii) synopsis of the individual and combined capabilities of the various unit operations in terms of separation performance and throughput capacity; (iii) preliminary calculations of mass and liquid flow rates based on data obtained from the pilot-scale test work, and (iv) a complete listing of key operating demands including power consumption, process water usage, and reagent requirements. Criteria used in evaluating process performance included product yield, product recovery, product quality, rejection levels, and separation efficiency. To ensure that the test data are reliable and self-consistent, the experimental data was analyzed and adjusted using a standard mass balance program. Experimental values that were deemed by the mass balance routines to be unreliable were removed from the data set.

Task 4 – Phase I Sample Analysis

Detailed analyses were conducted on each of the samples collected during the proposed test program. Unless otherwise specified, these analyses were performed in accordance with

ASTM procedures and standards. Representative samples were collected around the various pilot-scale unit operations. Mass and liquid flow rates from most streams were directly measured using hand samplers or mechanical flow meters. The mass and liquid flow rate of any stream that could not be directly measured was back-calculated from sample assays using the two-product formula.

Task 5 – Phase I Project Report

Technical Progress Reports for Phase I activities were prepared and submitted to DOE on a quarterly basis using a PowerPoint template (provided by DOE). In addition, a written Phase I Topical Report was provided to DOE after the completion of the Phase I activities (Tasks 1-5). The draft report included all major experimental data, engineering analyses, computations, test results, and major findings from the Phase I work.

2.3 Project Tasks for Phase II – Prototype Testing

Task 6 – Phase II Project Planning

This task, which was initiated after successfully completing Phase I, involved updating of the Project Work Plan to describe the work activities to be performed under Phase II. The revised plan identified the two test sites (one coal and one phosphate) for the installation of the production-scale prototype. An experimental test plan was also prepared to describe the sampling and analysis required to successfully complete the Phase II work.

Task 7 – Scale-up Design and Engineering

Subtask 7.1 (Flowsheet Design) involved the development of process flowsheets for the production-scale prototypes. The engineering and design work was completed as a coordinated effort between personnel from Eriez Manufacturing and the participating mining companies. Eriez Manufacturing was solely responsible for completing Subtask 7.2 (Equipment Design), which involved the final detailed design and engineering associated with the fabrication and construction of the prototype equipment.

Task 8 – Fabrication, Installation, Commissioning

This task involved the in-house fabrication of the prototype high-efficiency separators at the Eriez Manufacturing shop facility. Once fabrication was completed, the prototype units were transported to the mine sites and installed by the mining companies. All expenses associated with the purchase and installation of the prototype unit were completely covered by the participating mining companies. All project participants assisted in the final commissioning and shakedown testing of the prototype equipment.

Task 9 – Performance Testing

After completion of the commissioning work, detailed tests were conducted at each mine site in order to evaluate the capabilities of the prototype equipment. This effort, which included a wide variety of experimental test runs, required approximately three months of dedicated testing at each of the two test sites (one mineral and one coal). In each series of tests, representative samples of the product streams were collected and subjected to the appropriate analytical analysis procedures. When possible, data from existing plant separators were obtained and

compared with those obtained using the prototype equipment. Data logs were maintained by plant management to document improvements in separation performance, power consumption, process water usage, and reagent dosage.

Task 10 – Phase II Sample Analysis

Detailed analyses were conducted on each of the samples collected during the prototype test program. Unless otherwise specified, these analyses were performed in accordance with ASTM procedures and standards.

Task 11 – Technical Evaluation

The raw test data obtained from the testing of the prototype units was compiled and analyzed. A preliminary economic evaluation of the prototype installations was also carried out to assess the overall commercialization potential of the proposed high-efficiency hydraulic separators. Items examined in the economic evaluation included (i) total capital costs for the full-scale commercial installation of the proposed circuitry and any required ancillary operations and (ii) expected O&M costs including electrical power, reagents, and other consumables.

Task 12 – Final Project Report

Technical Progress Reports were prepared and submitted to DOE on a quarterly basis as PowerPoint files. In addition, Technical Progress Reports were submitted after completing Phase I (Pilot-Scale Testing, Tasks 1-5) activities and Phase II (Prototype Testing, Tasks 6-12) activities. Information from these documents was used to prepare the Final Project Report (the current document).

3.0 RESULTS AND DISCUSSION - PHASE I

3.1 Phase I Testing of Coal Plants

3.1.1 Testing at Coal Plant A

Initial field testing of the pilot-scale CrossFlow separator was conducted at Coal Plant A. This work involved (i) equipment setup, (ii) shakedown testing, and (iii) detailed testing. The goal of this effort was to determine the anticipated product yield and grade, combustible recovery, and feed capacity of the unit in order to predict the expected performance of a full-scale unit. Approximately 3 months of effort were allocated for field-testing.

The separator was transported from Eriez Manufacturing Central Research Lab in Erie, Pennsylvania, to the preparation plant. With cooperation from the operators and mechanics at the plant, a 9x16 inch pilot-scale CrossFlow separator was installed at the Coal Plant A. A splitter-box, fabricated at Eriez Manufacturing shop in Pennsylvania, was installed to collect the underflow of a classifying cyclone. The cyclones classify the raw feed with the overflow reporting to the froth flotation circuit and the underflow reporting to the water-only cyclones circuit. This splitter was fully adjustable and allowed for the easy regulation of feed rates. The feed sample was conveyed by gravity through a 2-inch line to the CrossFlow separator that was positioned one level below the classifying cyclone. Underflow and overflow material from the separator was discharged to sizing screens in the plant, located on a level below the unit.

Plant compressed air and 115 volt electrical power were connected to the separator for the automated control system. The separator was automatically controlled through the use of a simple PID control loop which includes a pressure sensor mounted on the side of the separator to measure the relative pressure (level), a single loop PID controller, and a pneumatic pinch valve to control the underflow discharge to maintain a constant bed pressure (level). Clarified water

was connected to the separator to create the fluidized teeter bed of solids. After completing the installation of the test unit, preliminary shakedown testing was conducted to resolve any unexpected operational problems that could arise. These tests were necessary to resolve any problems that may have been overlooked in the initial engineering and to confirm that feed capabilities, pipe sizes, electrical supplies, control systems, etc., were adequate. In addition, these tests provided an opportunity to establish approximate settings for the various process variables required to provide good separation performance based on visual inspections of the products.

Two series of detailed test programs were conducted using the pilot-scale CrossFlow unit. The first series of tests were performed to investigate the effects of the key design variables on separator performance. Important test variables included: feed injection depth and distributor design. In addition to determining the optimum operating variables, the first series of test simultaneously defined the overall grade and recovery curve for the process. The subsequent round of testing was used to investigate the effects of key operating parameters. The variables examined included: (i) fluidization water rate, (ii) solids mass feed rate, (iii) volumetric slurry feed rate, and (iv) teeter bed depth. A minimum of three settings were examined for each of the listed test parameters. For each test, samples were taken from the feed, overflow, and underflow streams after conditions were stabilized. Each sample was analyzed for ash and sulfur (in many cases on a size-by-size basis).

Due to the low amount of rock present in this feed, a higher feed rate was determined to be acceptable for this application and was utilized in much of the testing. Feed rates ranged from a low of 1 tph/ft² to a high of 5 tph/ft². The feed percent solids were reasonably constant at 40%-50% throughout the test period. A significant difference in the feed for each series of testing

must be noted as the average ash content for the first series was nearly 14.0% while the average ash content for the second series was only 10.5%.

The as-tested coal slurry was found to have a mean particle size of 0.631 mm during the first series of testing and 0.572 mm during the second series of testing. The solids specific gravity was measured to be 1.55 with a solids content of 50%. The feed size distribution is summarized in Table 3.1. Table 3.2 provides a summary of the operating parameters that were

Table 3.1. Feed size distribution of Coal Plant A.

Size Class (Mesh)	Round 1		Round 2	
	(% in Class)	(% Ash)	(% in Class)	(% Ash)
+10	2.38	14.02	1.21	6.67
10x14	8.48	10.94	6.92	7.09
14x28	38.89	11.77	34.89	7.27
28x60	26.53	11.45	29.56	8.60
60x100	11.49	12.99	10.38	9.69
-100	12.23	28.28	17.04	21.89
Overall	100.00	13.83	100.00	10.39

Table 3.2. Operating parameters for on-site pilot-scale testing at Coal Plant A.

Round	Test No.	Feed Flow (gpm)	Feed Pump (SG)	Feed Solids (%)	Feed Rate (tph/ft ²)	Teeter Water (gpm)	Bed Level No.
1	1	10.0	1.17	40.9	1.2	6	64
	2	10.0	1.17	40.9	1.2	6	64
	3	9.2	1.18	43.0	1.2	6	99
	4	9.7	1.17	39.9	1.1	6	97
	5	9.8	1.17	40.9	1.2	6	95
	6	9.8	1.16	38.9	1.1	6	96
	7	12.6	1.17	39.9	1.5	6	96
	8	12.7	1.18	43.0	1.6	6	92
2	9	30.0	1.21	48.9	4.4	7	94
	10	35.3	1.20	47.0	5.0	7	92
	11	33.3	1.20	46.4	4.6	7	93
	12	28.6	1.20	47.0	4.0	7	94
	13	28.6	1.20	47.0	4.0	7	94
	14	20.0	1.19	44.0	2.6	7	90

investigated during both rounds of testing. To ensure the test data was reliable and self-consistent, all test data was analyzed and adjusted using mass balance software. Experimental values that were deemed by the mass balance routines to be unreliable were removed from the data set. The participating mining company used the compiled data to establish the metallurgical improvement, operating savings and economic payback that may be realized by implementing the proposed high-efficiency technologies.

The results from the on-site CrossFlow separator investigation are shown graphically in Figures 3.1 through 3.3. The results are summarized as: “As-Tested” and “x 100 Mesh” with the passing 100-mesh material mathematically removed from the data. This approach is acceptable as it is expected that the clean coal product will be deslimed at approximately 0.150 mm. The material finer than 100 mesh will be upgraded by flotation at this particular plant.

As presented in Figure 3.1, this pilot-scale test work was able to define the expected

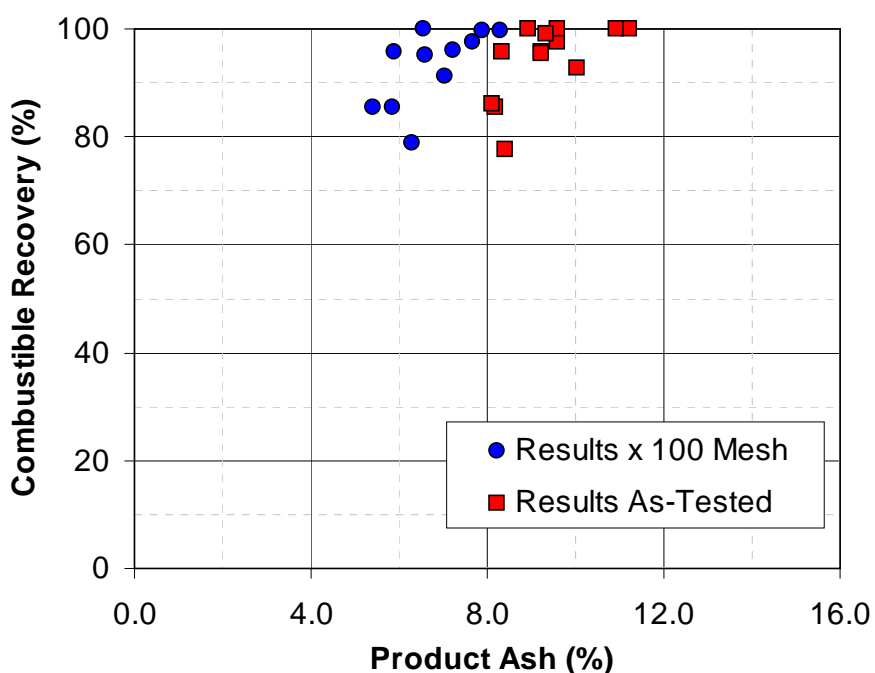


Figure 3.1. Combustible recovery vs. product ash content for Coal Plant A.

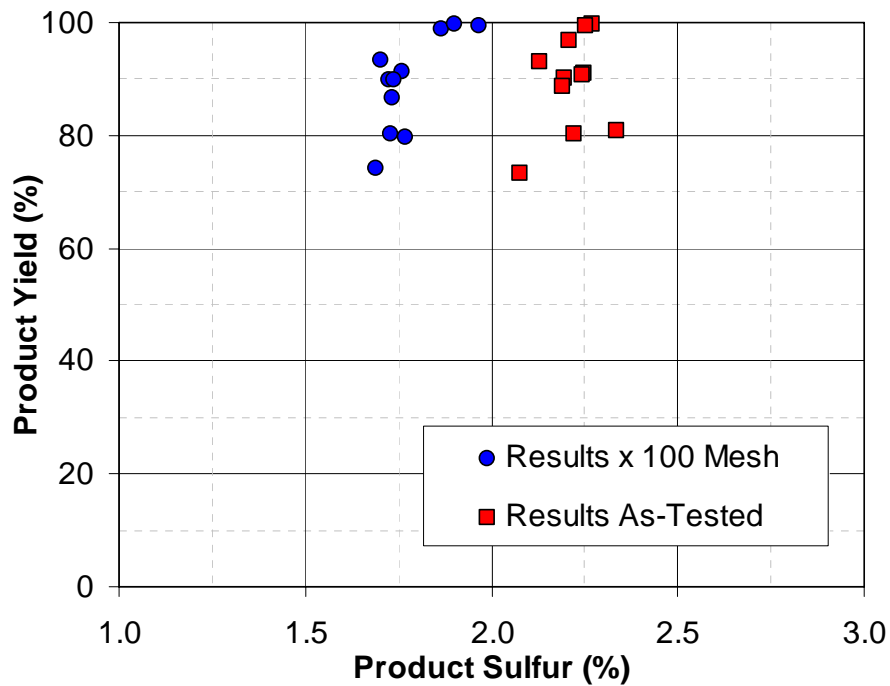


Figure 3.2. Mass yield vs. product sulfur content for Coal Plant A.

grade and recovery curve for this particular coal. Specifically, the CrossFlow separator is capable of providing a clean product ranging between 6% and 8% ash at a combustible recovery of greater than 95% (when deslimed at 100 mesh). At maximum separation efficiency, the combustible recovery, for this application, approached 98%. The data presented in Figure 3.2 indicates that the sulfur content of the corresponding product will be approximately 1.75%.

Figure 3.3 is included to demonstrate the ability of the CrossFlow separator to provide high combustible recoveries even when operated at elevated throughput rates. During the second series of testing, the feed rate was increased to a very high value of 5 tph/ft². During this time, the combustible recovery remained unaffected. It must also be noted that the feed ash during this second series of testing was significantly lower than the first series of testing, resulting in product yields greater than 96%. Simply stated, there was not a significant amount of rock

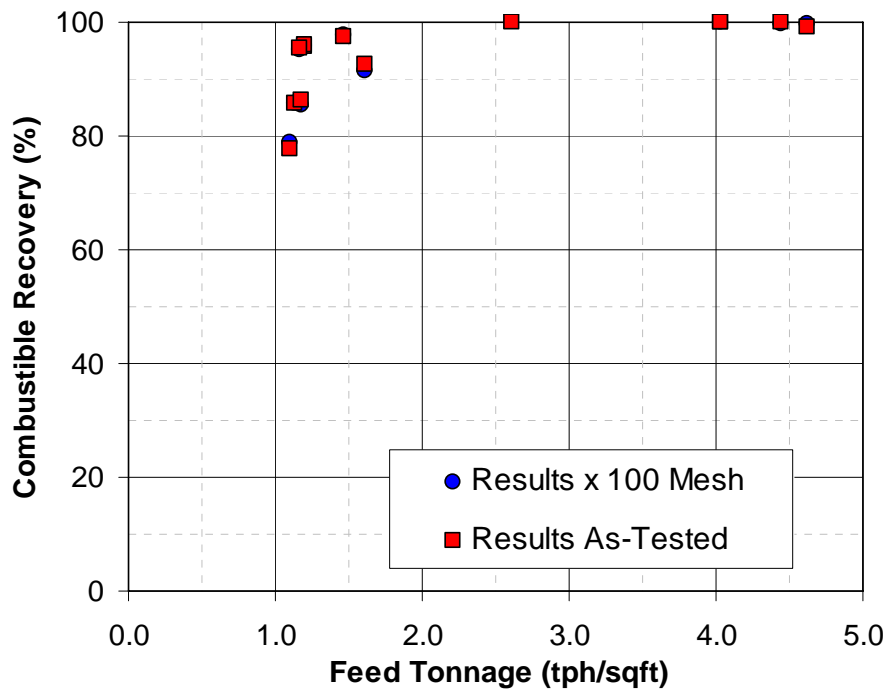


Figure 3.3. Combustible recovery vs. feed tonnage for Coal Plant A.

present in the feed stream. Regardless, the CrossFlow separator was able to produce a tailings stream with an ash content averaging 76.5% and a corresponding sulfur content averaging 12.20% for this particular feed coal.

The material balance presented in Figure 3.4 is included as a summary of the test work conducted at the Coal Plant A. This material balance includes all expected metallurgical results, ancillary requirements, and volumetric flows for a full-scale installation with the capacity to treat 150 tph of feed at approximately 50% solids (by weight). For this duty, a 7x7-ft CrossFlow separator has been recommended for the operation, offering 49 ft² of cross-sectional area which results in a normalized feed rate of 3 tph/ft². The current test work has demonstrated the ability of the CrossFlow separator to handle this entire flow in a single stage circuit.

CROSSFLOW CIRCUIT - MATERIAL BALANCE

150.0 tph Option

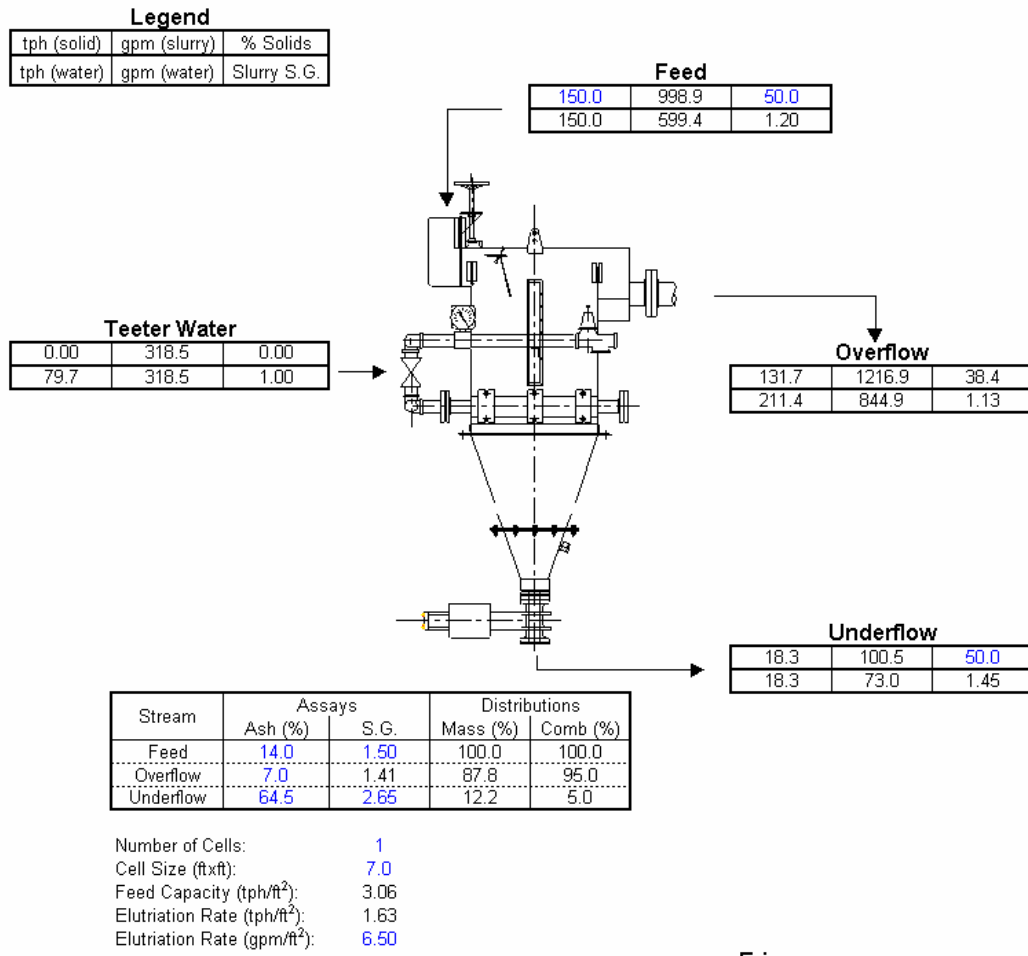


Figure 3.4. Material balance for a CrossFlow separator treating 150 tph.

3.1.2 Testing at Coal Plant B

The next set of field-tests with the pilot scale CrossFlow separator were carried out at a second coal plant (Plant B). As before, this work involved (i) equipment setup, (ii) shakedown testing, and (iii) detailed testing. In this particular case, the goal of this effort was to determine the anticipated product yield and grade, combustible recovery, and feed capacity of the unit for comparison against the existing spiral circuit. Approximately 3 months of effort were allocated

for field-testing. Individuals from Eriez Manufacturing and Virginia Tech participated in the testing at Coal Plant B with cooperation from key personnel at the processing plant.

The separator was transported from the Coal and Minerals Research Lab at Virginia Tech in Blacksburg, Virginia to the preparation plant. The 9x16 inch pilot-scale CrossFlow separator was installed at the Coal Plant B as shown in Figure 3.5. Feed was supplied to the CrossFlow separator through a 2 inch line connected to existing coal spiral slurry feed distributor. A slurry splitter fabricated from PVC pipe with a tee and valves was used to regulate the feed to the unit, with the remaining slurry reporting to the spiral circuit. Underflow and overflow material was discharged to sizing screens in the plant, located on a level below the unit.

Plant compressed air and 115 volt electrical power were connected to the separator for



Figure 3.5. The 9x16 inch pilot-scale Crossflow circuit at Coal Plant B.

the automated control system. The separator was automatically controlled through the use of a simple PID control loop which includes a pressure sensor mounted on the side of the separator to measure the relative pressure (level), a single loop PID controller, and a pneumatic pinch valve to control the underflow discharge to maintain a constant bed pressure (level). Clarified water was connected to the separator to create the fluidized teeter bed of solids.

After completing the installation of the test unit, preliminary shakedown testing was conducted to resolve any unexpected operational problems that could arise. These tests were necessary to resolve any problems that may have been overlooked in the initial engineering and to confirm that feed capabilities, pipe sizes, electrical supplies, control systems, etc., were adequate.

Two series of detailed test programs were conducted using the pilot-scale test unit. The first series of tests were performed to investigate the effects of the key design variables on separator performance and to simultaneously define the overall grade and recovery curve. The subsequent series of testing was performed to investigate the effects of key operating parameters. Tests were conducted primarily as a function of teeter bed pressure and fluidization water rate. The coal/rock interface, or teeter bed, was adjusted to different levels (i.e. different bed pressure) for each steady-state test. Fluidization water was adjusted to fine tune the separation. Other variables considered were solids mass feed rate and volumetric slurry feed rate. For each test, samples were taken from the feed, overflow, and underflow streams after conditions were stabilized. The samples were analyzed for ash and sulfur (by-size).

Six test runs were completed during the on-site test work. Additionally, a set of samples was taken with regard to the existing coal spirals. The spiral samples were collected during the same time frame as tests #3, #4, and #5 of the CrossFlow separator evaluation.

The particles in the feed slurry were found to have a mean diameter of 0.406 mm. The solids specific gravity was measured to be 1.55. Feed percent solids ranged between 35% and 40% and the feed rate varied from 2.0-2.8 tph/ft². The feed size distribution is summarized in Table 3.3. Table 3.4 is a summary of the array of operating parameters that were investigated during testing. To ensure the test data was reliable and self-consistent, all as-received results were analyzed and adjusted using mass balance software. Experimental values that were deemed by the mass balance routines to be unreliable were removed from the data set. The participating mining company used the compiled data to establish the metallurgical improvement, operating savings and economic payback that may be realized by implementing the proposed high-

Table 3.3. Feed size distribution of Coal Plant B.

Stream Description	Passing	Size Retained	Mean	Weight (%)	Ash (%)
Plus 16 M	***	1.000	1.000	6.24	9.94
16x32 M	1.000	0.500	0.707	23.87	11.23
32x60 M	0.500	0.250	0.354	29.38	12.53
60x100 M	0.250	0.150	0.194	22.54	13.75
Minus 100 M	0.150	***	0.150	17.97	39.17
Composite			0.406	100.00	17.12

Table 3.4. Operating parameters for on-site pilot-scale testing at Coal Plant B.

Unit Operation	Test Number	% Solids	Feed tph	gpm	Level inches	Water gpm
CrossFlow	XF1	35.5	2.01	21.90	6.0	4.76
CrossFlow	XF2	36.3	2.38	23.35	12.0	4.76
CrossFlow	XF3	38.5	2.83	26.06	8.0	3.61
CrossFlow	XF4	37.2	2.56	24.79	8.0	4.72
CrossFlow	XF5	35.8	2.49	25.02	8.0	5.51
CrossFlow	XF6	38.1	2.48	24.37	8.0	4.44
Spiral*	7	38.0	3.50	32.70	n/a	n/a

* Samples taken during tests 3, 4 and 5

* Multiple starts, 3 product screen feed, 1 reject screen feed

efficiency technologies.

The as-received results, as analyzed and adjusted using a mass balance program, are reported in Table 3.5. The products were sized at 100 mesh so that each fraction could be evaluated separately. As expected, the minus 100 mesh product had a higher ash content than the plus 100 mesh fraction. This is expected as fine material, especially passing 150 mesh, tends to

Table 3.5. In-plant test results for Coal Plant B.

Size Fraction	Test Number	Mass Yield (%)	Ash Assay (%)	Sulfur Assay (%)	Comb Rec (%)	Sulfur Rec (%)	Ash Rej (%)	Sulfur Rej (%)
Plus 100 Composite Feed	XF1	96.04	10.06	4.07	98.80	92.60	23.19	7.40
	XF1	96.54	15.80	5.16	98.91	94.54	14.38	5.46
	XF1	100.00	17.81	5.27	100.00	100.00	0.00	0.00
Plus 100 Composite Feed	XF2	96.22	9.25	3.97	98.50	93.46	21.56	6.54
	XF2	96.80	15.00	4.99	98.67	95.18	12.59	4.82
	XF2	100.00	16.61	5.08	100.00	100.00	0.00	0.00
Plus 100 Composite Feed	XF3	94.09	10.03	4.04	97.94	89.91	30.48	10.09
	XF3	94.87	15.48	5.16	98.14	92.40	19.72	7.60
	XF3	100.00	18.30	5.30	100.00	100.00	0.00	0.00
Plus 100 Composite Feed	XF4	96.16	9.76	4.04	98.75	92.73	22.61	7.27
	XF4	96.76	14.75	5.17	98.90	94.82	13.98	5.18
	XF4	100.00	16.60	5.28	100.00	100.00	0.00	0.00
Plus 100 Composite Feed	XF5	96.70	10.12	4.05	99.17	94.39	20.78	5.61
	XF5	97.21	16.18	5.33	99.25	96.07	12.14	3.93
	XF5	100.00	17.90	5.39	100.00	100.00	0.00	0.00
Plus 100 Composite Feed	XF6	97.03	10.11	4.06	99.26	94.30	19.16	5.70
	XF6	97.47	15.19	5.35	99.34	96.04	11.79	3.96
	XF6	100.00	16.78	5.43	100.00	100.00	0.00	0.00
Plus 100 Composite Feed	Spiral	92.32	8.82	4.08	97.10	87.91	38.82	12.09
	Spiral	90.56	13.75	5.00	96.19	81.84	33.77	18.16
	Spiral	100.00	18.80	5.53	100.00	100.00	0.00	0.00

report to the separator overflow due to its relatively small mass. In essence, the teeter water overcomes the settling velocity of these particles and flushes them out of the separator. As such, the results in this report are compared on a plus 100 mesh basis. This is acceptable as the existing circuit incorporates dewatering screens for each of the product streams.

The results from the pilot-scale CrossFlow separator investigation are shown graphically in Figure 3.6 for the +100 mesh material. The results of the CrossFlow separator are comparable to the existing coal spirals. Upon close examination (Figure 3.6 inset), when compared to the coal spirals, the CrossFlow separator provides a marginally better clean coal yield at 96% vs. 92%. However, the higher product yield also generates a product with slightly higher ash content

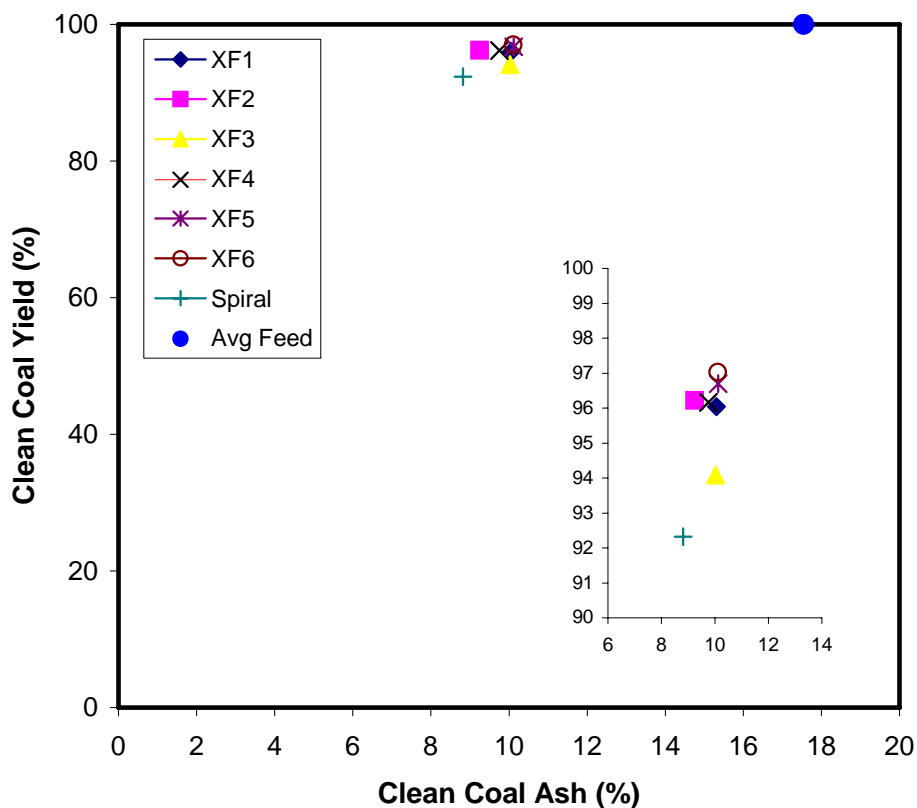


Figure 3.6. Yield vs. clean coal ash for +100 mesh size fraction at Coal Plant B.

at 9.25-10.00% vs. 8.8%. Lower product ash values are possible using the CrossFlow separator and can be achieved through lower fluidization rates and/or bed pressures.

Data in Figures 3.7 and 3.8 shows the size-by-size results from Table 3.5 graphed by size class. In these charts, the left most (i.e., lowest ash and sulfur) data points correspond to the plus 100 mesh size fraction. The data points in the middle position represent the composite (100 mesh x 0) size fraction. The right-most data points (shown at 100% yield) correspond to the feed grade.

The data demonstrate that for any given product ash content or sulfur content, the CrossFlow separator can produce a higher clean coal yield when compared to the existing coal

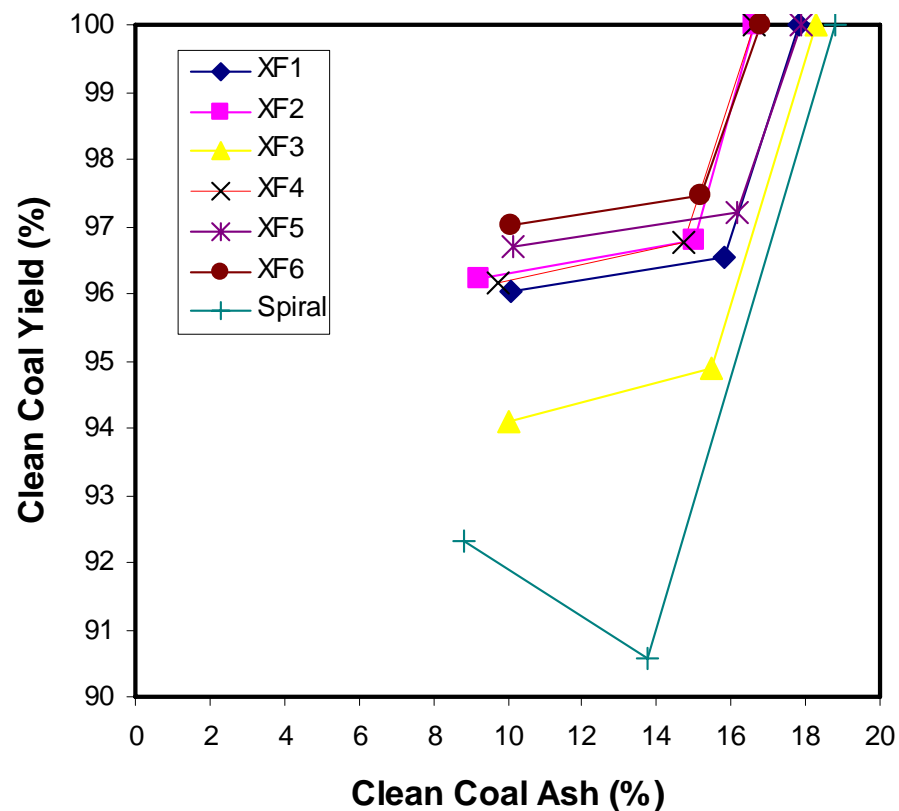


Figure 3.7. Performance for +100 mesh and composite samples at Coal Plant B.

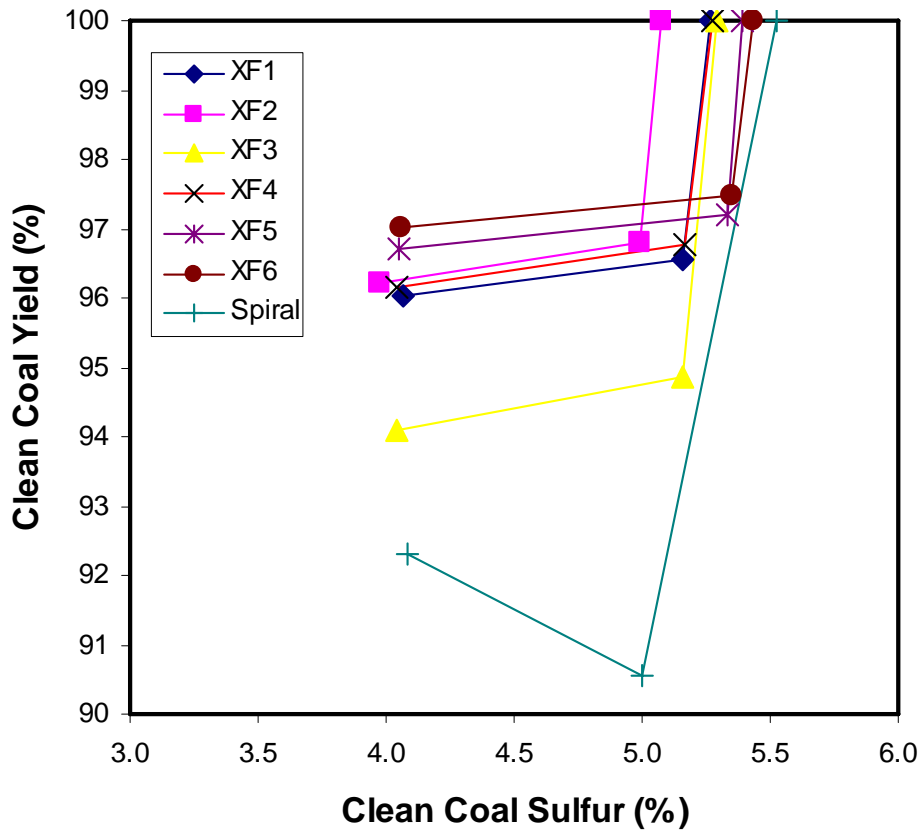


Figure 3.8. Performance for +100 mesh and composite samples at Coal Plant B.

spirals. Essentially, at 10% product ash content, the CrossFlow separator operates with a clean coal yield ranging between 96% and 97%, while the spirals produce a yield of approximately 92%. It should be noted that a 4% difference in clean coal yield for a 200 tph circuit can represent a \$1,400,000 per year (i.e., 200 tph x 7000 hr/yr x \$25/ton x (Yield_{CF} - Yield_S)). A similar trend is also shown when examining the sulfur data (Figure 3.8).

Results indicate that the performance of the CrossFlow separator was equal or superior to the performance of the existing spiral circuit for this preparation plant. The material balance presented in Figure 3.9 is included as a summary of the test work conducted at the Coal Plant B. The material balance includes all expected metallurgical results, ancillary requirements, and

CROSSFLOW CIRCUIT - MATERIAL BALANCE

200.0 stph Option

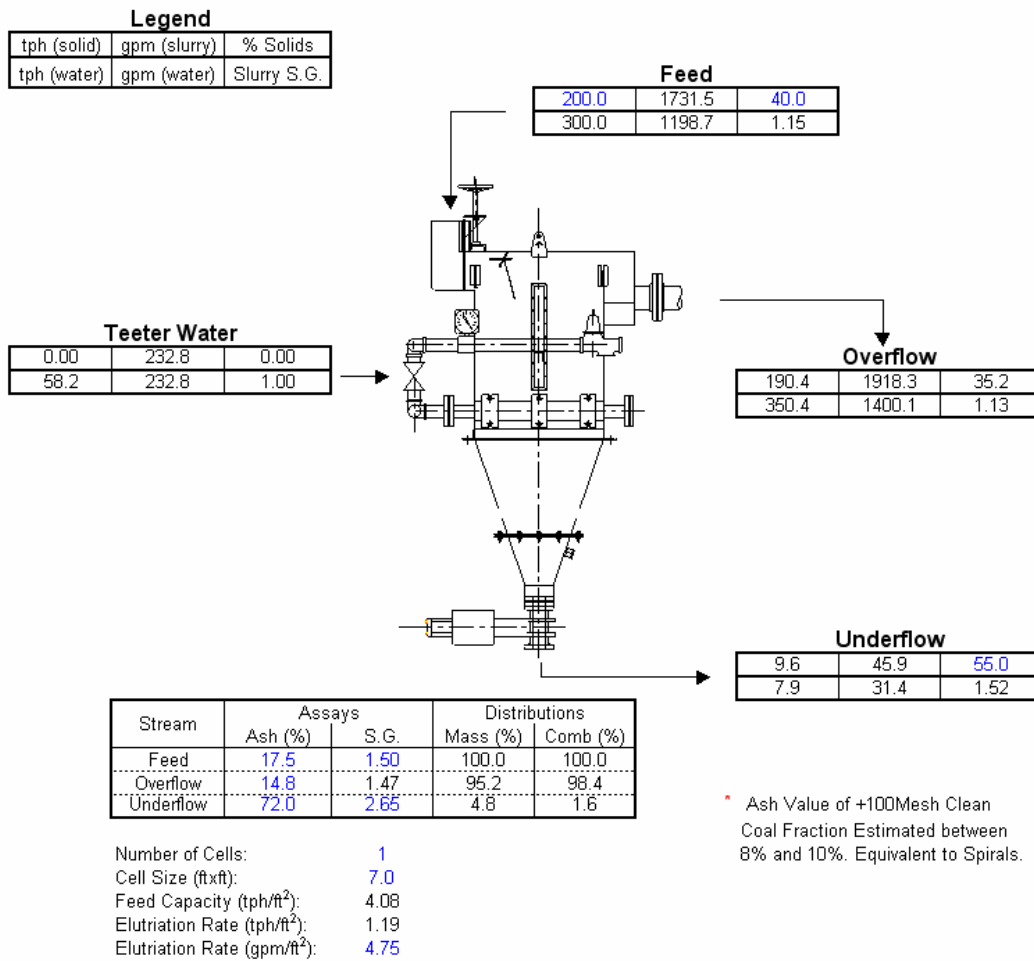


Figure 3.9. Material balance for two 7x7 ft CrossFlow separators.

volumetric flows for a full-scale installation capable of treating the required 200 tph flow with one 7x7-ft CrossFlow separator.

3.1.3 Testing at Coal Plant C

Additional field testing of the CrossFlow separator was performed for Coal Plant C. This work involved equipment setup, shakedown and detailed testing. The goal of this particular effort was to determine the anticipated product yield and grade, combustible recovery, and feed

capacity of the unit. In this case, the CrossFlow separator was to be evaluated as a potential replacement for an existing single-stage spiral circuit. Approximately 3 months of effort were allocated for field-testing at this site. Individuals from Virginia Tech and University of Kentucky participated in the testing at Coal Plant C with cooperation from key personnel at the processing plant.

The CrossFlow separator was transported from the University of Kentucky in Lexington, Kentucky, to the preparation plant. With cooperation from the operators and mechanics at the plant, the 12-inch diameter pilot-scale CrossFlow separator was installed at the Coal Plant C (see Figure 3.10). Feed was supplied to the CrossFlow separator through a 2-inch line by connecting to an existing coal slurry spiral feed distributor. A slurry splitter fabricated from PVC pipe with a



Figure 3.10. The 12-inch diameter pilot-scale CrossFlow circuit at Coal Plant C.

tee and valves was used to regulate the feed to the unit, with the remaining slurry reporting to the spiral circuit. Underflow and overflow material was discharged to the spiral underflow launders.

As with the other test sites, plant compressed air and 115 volt electrical power were connected to the separator for the automated control system. The separator was automatically controlled through the use of a simple PID control loop which includes a pressure sensor mounted on the side of the separator to measure the relative pressure (level), a single loop PID controller, and a pneumatic pinch valve to control the underflow discharge to maintain a constant bed pressure (level). Clarified water was connected to the separator to create the fluidized teeter bed of solids.

After installation was complete, preliminary shakedown testing of the unit was conducted to resolve any unexpected operational problems that could arise. These tests were designed to resolve any problems that may have been overlooked in the initial engineering and to confirm that feed capabilities, pipe sizes, electrical supplies, control systems, etc., were adequate.

Two series of detailed test programs were conducted using the pilot-scale test unit. The first series of tests were performed to investigate the effects of the key design variables on separator performance and to simultaneously define the overall grade and recovery curve. The subsequent series of testing was used to investigate the effects of key operating parameters. Tests were conducted primarily as a function of teeter bed pressure and fluidization water rate. The coal/rock interface, or teeter bed, was adjusted to different levels (i.e. different bed pressure) for each steady-state test. Other variables that were considered were solids mass feed rate and volumetric slurry feed rate. For each test, samples were taken from the feed, overflow, and underflow streams after conditions were stabilized. Each sample was sized and analyzed for ash and sulfur contents.

Nine test runs were completed during the on-site test work conducted at Coal Plant C. Table 3.6 is a summary of the operating parameters that were investigated during testing. The set point transition between tests #4 and #5 is due to recalibration of the control system. The difference in the set point when treating the Seam A and Seam B is due to the particle size distribution difference and the desire to maintain a constant bed height. Additionally, samples were collected from the process streams of the existing coal spirals when treating the Seam A and Seam B fine coal.

To ensure the test data was reliable and self-consistent, all as-received results were analyzed and adjusted using mass balance software. Experimental values that were deemed by the mass balance routines to be unreliable were removed from the data set. The participating mining company used the compiled data to establish the metallurgical improvement, operating savings and economic payback that may be realized by implementing the proposed high-efficiency technologies.

The Coal Plant C treats coal from both the coal seams separately. As such, the teeter-bed

Table 3.6. Operating parameters for on-site pilot scale testing at Coal Plant C.

Test	Seam	Set Point	Solid Density (%)	Feed				
				Pulp Density (gm/cm ³)	Solids (%)	Rate		
						gpm	tph	tph/ft ²
1	B	46	1.6	1.088	21.57	12	0.7	0.4
2	A	46	1.6	1.13	30.68	14	1.21	0.69
3	A	46	1.6	1.09	22.02	11.65	0.7	0.4
4	A	45	1.6	1.09	22.02	12.32	0.74	0.42
5	B	78	1.6	1.1	24.24	9.83	0.66	0.37
6	B	79	1.6	1.13	30.68	9.49	0.82	0.47
7	A	87	1.6	1.125	29.63	19.47	1.62	0.92
8	A	88	1.6	1.1	24.24	16.22	1.08	0.61
9	B	80	1.6	1.13	30.68	10.5	0.91	0.52

unit was evaluated for the cleaning potential of the nominal 16 x 100 mesh fractions of both coals. Feed percent solids ranged between 22% and 30% during the test program, with variations in the mass feed rate to the unit varying from 0.37-0.92 tph/ft². Samples of the feed to the teeter-bed unit were taken and subjected to washability and particle size analysis. The washability data indicates that both coals can be classified as ‘easy-to-clean’ based on their relatively low contents of middling material, their cumulative float ash contents of less than 5%, and combustible recovery greater than 95%. The difference in the two coals is that the Seam B coal produces a one percentage point lower float ash content.

The particle size distribution of Seam B feed coal was significantly finer than the Seam A coal as shown in Table 3.7. The minus 100 mesh fraction was removed from the particle size analysis since the concentration on cleaning potential was isolated on the plus 100 mesh material. Both coals only had 1% to 2% by weight of plus 16 mesh material in the feed. However, the Seam B material had nearly 12 percentage points less of the coarsest plus 28 mesh size fraction. This finding explained the need to operate at this particular site at lower bed pressure settings in order to maintain the same fluidized particle bed height. The distributions of the ash-bearing material in both coals are nearly equivalent.

The CrossFlow unit achieved excellent separation performances for both feed coals as

Table 3.7. Feed size distribution for Coal Plant C.

Particle Size (Mesh)	Seam B		Seam A	
	Weight (%)	Ash (%)	Weight (%)	Ash (%)
+28	16.98	15.63	29.20	17.28
28 x 48	35.98	18.38	31.56	19.30
48 x 100	47.04	19.51	39.24	19.20
Total	100.00	18.44	100.00	18.67

shown in Table 3.8 and Figure 3.11. For the Seam B coal, the ash content was reduced from 17.57% to a value as low as 6.51% while recovering 97% of the combustible material. Similar performances were achieved on the Seam A coal with product ash values as low as 7.51%. The performances from eight of the nine tests were very close to ideal as indicated by the comparison with the washability data in Figure 3.11. The teeter-bed performances compare favorably with those achieved by the existing spiral circuit shown in Table 3.9.

The size-by-size performance of the test unit is shown in Tables 3.10 and 3.11 for the Seam B and Seam A coals, respectively. These results indicate that the teeter-bed unit performed exceptionally well on the plus 28 mesh and the 28 x 48 mesh particle size fractions. For example, a 2.87% product ash was achieved from the plus 28 mesh Seam B coal, while the tailings ash content was maintained at a relatively high 72.26%. However, the separation density appears to shift upward significantly with a decrease in particle size as evident by the higher product ash contents in the 48 x 100 mesh particle size fractions of both coals.

Table 3.8. CrossFlow separation performances at Coal Plant C.

Test Number	Ash (%)			Yield (%)	Recovery (%)
	Feed	Product	Tailing		
1	19.96	9.97	86.67	86.97	97.83
2	20.54	14.55	86.88	91.71	98.63
3	18.99	8.45	82.06	85.68	96.83
4	24.05	10.01	76.51	78.89	93.47
5	17.57	6.51	84.08	85.74	97.25
6	17.57	7.69	86.43	87.45	97.93
7	21.44	13.45	86.43	89.06	98.11
8	21.21	8.86	83.25	83.40	96.47
9	23.43	7.51	50.09	62.61	75.63

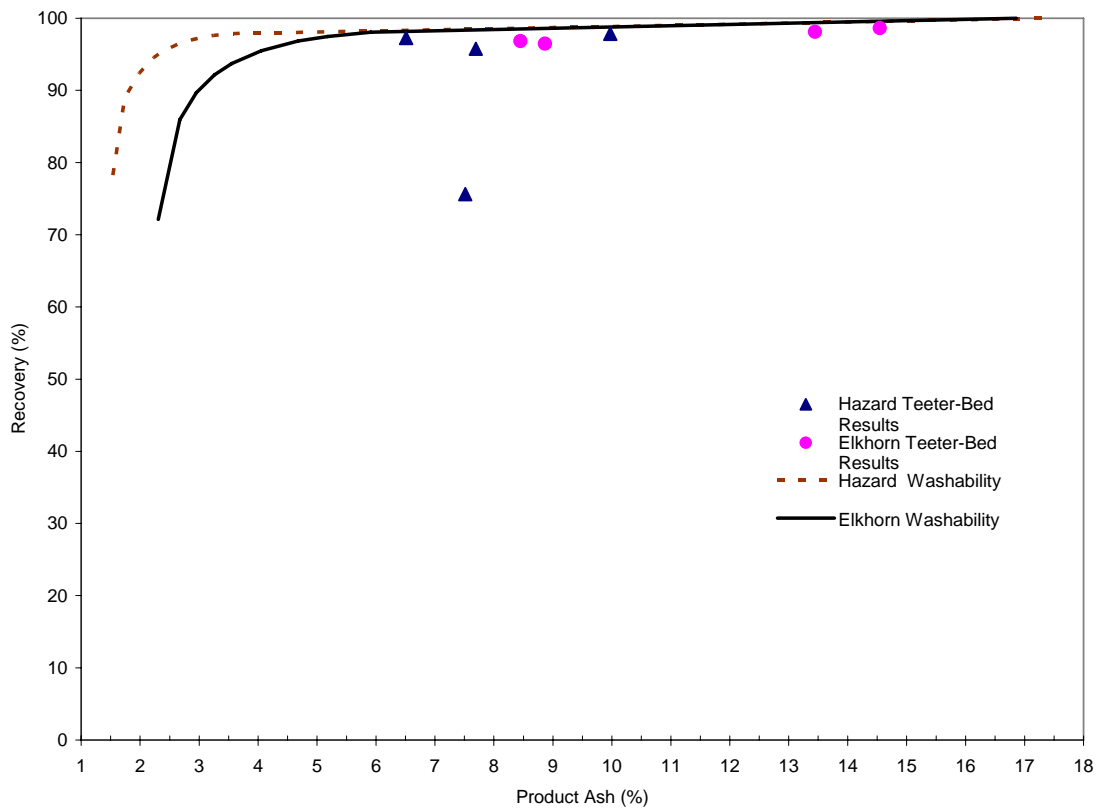


Figure 3.11. Comparison of separation performance and washabilities at Coal Plant C.

3.1.4 Testing at Coal Plant D

The next coal plant involved in the field-testing of the pilot-scale CrossFlow separator was Coal Plant D. As with the other test sites, this work involved (i) equipment setup, (ii) shakedown testing, and (iii) detailed testing. The goal of this effort was to determine the anticipated product yield and grade, combustible recovery, and feed capacity of the test unit in order to predict the expected performance of a full-scale unit. In this particular case, the testing was performed to determine whether the installation of one or more full-scale units could be justified at a new green-field plant in Kentucky. Approximately 3 months of effort were

Table 3.9. Separation achieved by the existing spiral circuit at Coal Plant C.

Test Number	Seam	Ash (%)			Yield (%)	Recovery (%)
		Feed	Product	Tailing		
1	SEAM B	17.57	5.22	85.51	84.61	97.29
2	SEAM A	21.44	7.49	85.07	82.03	96.58

Table 3.10. Size-by-size performance for Seam B fine coal at Coal Plant C.

Particle Size (Mesh)	Feed		Product		Tailings		Yield (%)	Recovery (%)
	Weight (%)	Ash (%)	Weight (%)	Ash (%)	Weight (%)	Ash (%)		
+ 28	16.98	15.63	17.32	2.87	22.74	72.26	81.61	93.95
28 x 48	35.98	18.38	44.87	4.53	49.12	85.86	82.97	97.05
48 x 100	47.04	19.51	37.81	11.70	28.14	89.96	82.97	98.76
Total	100.00	18.44	100.00	6.95	100.00	83.92	85.07	97.06

Table 3.11. Size-by-size performance for Seam A fine coal at Coal Plant C.

Particle Size (Mesh)	Feed		Product		Tailings		Yield (%)	Recovery (%)
	Weight (%)	Ash (%)	Weight (%)	Ash (%)	Weight (%)	Ash (%)		
+ 28	29.20	17.28	22.38	5.01	44.45	74.48	82.34	94.55
28 x 48	31.56	19.30	34.84	7.66	38.69	84.48	84.85	97.09
48 x 100	39.24	19.20	42.78	12.03	16.86	87.81	90.54	98.57
Total	100.00	18.67	100.00	8.94	100.00	80.60	86.42	96.76

allocated for field-testing. Individuals from Eriez Manufacturing participated in the testing at Coal Plant D with cooperation from key personnel at the preparation plant.

The CrossFlow separator was transported from Eriez Manufacturing Central Research Lab in Erie, Pennsylvania to the preparation plant. The 9x16 inch pilot-scale CrossFlow separator was installed at the Coal Plant D (as shown in Figure 3.12), with the cooperation from the operators and mechanics at the plant. Feed was supplied to the CrossFlow separator through a



Figure 3.12. The 9x16-inch pilot-scale CrossFlow circuit at Coal Plant D.

2 inch line connected to the existing coal spiral slurry feed distributor. A slurry splitter fabricated from PVC pipe with a tee and valves was used to regulate the feed to the unit, with the remaining slurry reporting to the spiral circuit. Underflow and overflow material was discharged to sizing screens in the plant, located on a level below the unit.

Plant compressed air and 115 volt electrical power were connected to the separator for the automated control system. The separator was automatically controlled through the use of a simple PID control loop which includes a pressure sensor mounted on the side of the separator to measure the relative pressure (level), a single loop PID controller, and a pneumatic pinch valve to control the underflow discharge to maintain a constant bed pressure (level). Clarified water was connected to the separator to create the fluidized teeter bed of solids.

Preliminary shakedown testing was conducted after completing the installation of the test unit to resolve any unexpected operational problems that could arise. These tests were conducted to resolve any problems that may have been overlooked in the initial engineering and to confirm that feed capabilities, pipe sizes, electrical supplies, control systems, etc., were adequate.

Two series of detailed test programs were conducted using the pilot-scale test unit. The first series of tests were performed to investigate the effects of the key design variables on separator performance and to simultaneously define the overall grade and recovery curve. The subsequent series of testing was performed to investigate the effects of key operating parameters. Tests were conducted primarily as a function of teeter bed pressure and fluidization water rate. The coal/rock interface, or teeter bed, was adjusted to different levels (i.e. different bed pressure) for each steady-state test. Fluidization water was adjusted to fine tune the separation. Other variables considered were solids mass feed rate and volumetric slurry feed rate. For each test, samples were taken from the feed, overflow, and underflow streams after conditions were stabilized. The samples were analyzed for ash and sulfur contents on a size-by-size basis.

To ensure the test data was reliable and self-consistent, all test data was analyzed and adjusted using mass balance software. Experimental values that were deemed by the mass balance routines to be unreliable were removed from the data set. The participating mining company used the compiled data to establish the metallurgical improvement, operating savings and economic payback that may be realized by implementing the proposed high-efficiency technologies.

Nine test runs were completed during the on-site test work.. The parameters of these tests are summarized in Table 3.12. The results from the on-site CrossFlow separator investigation are shown graphically in Figures 3.13 and 3.14. The results are summarized as: “As-Tested” and “x

Table 3.12. Operating parameters for on-site pilot-scale testing at Coal Plant D.

Test Number	% Solids	Feed tph	gpm	Level inches	Water gpm
1	32.55	1.83	20	14.5	8
2	34.44	1.95	20	20.0	8
3	35.24	2.00	20	10.0	8
4	35.71	1.73	17	10.0	9.5
5	32.90	2.22	24	14.5	9.5
6	32.71	1.84	20	20.0	9.5
7	35.21	2.00	20	20.0	6.5
8	34.10	1.93	20	14.5	6.5
9	33.55	1.89	20	10.0	6.5

100 Mesh” with the passing 100 mesh material mathematically removed from the data. This approach is acceptable as it is expected that the clean coal product will be deslimed at approximately 0.150 mm and the fine material upgraded by flotation.

As shown in Figure 3.13, this pilot-scale test work was able to define the expected grade

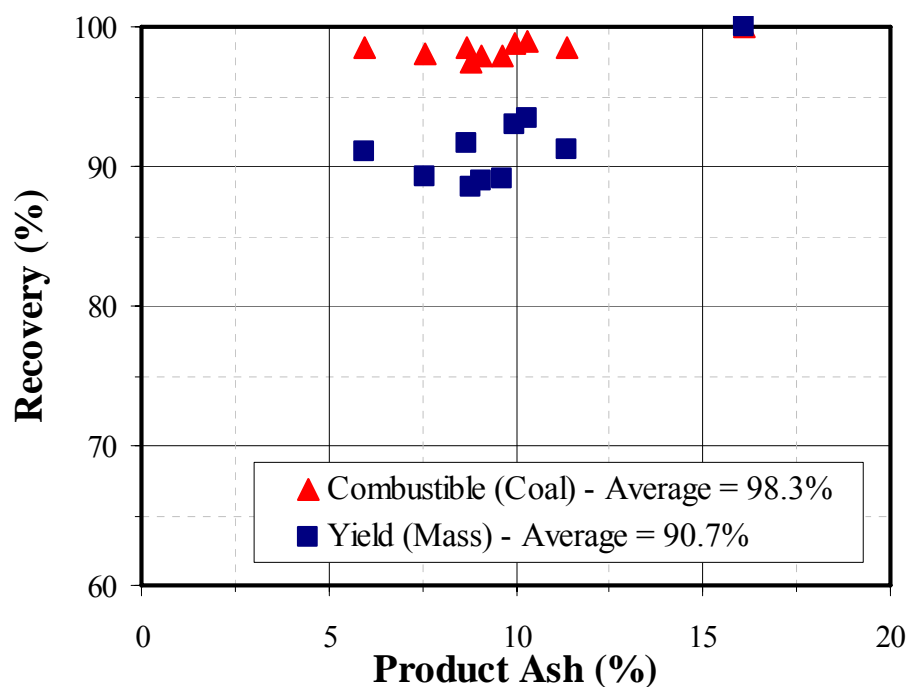


Figure 3.13. Recovery vs. product ash content of +100 mesh coal at Coal Plant D.

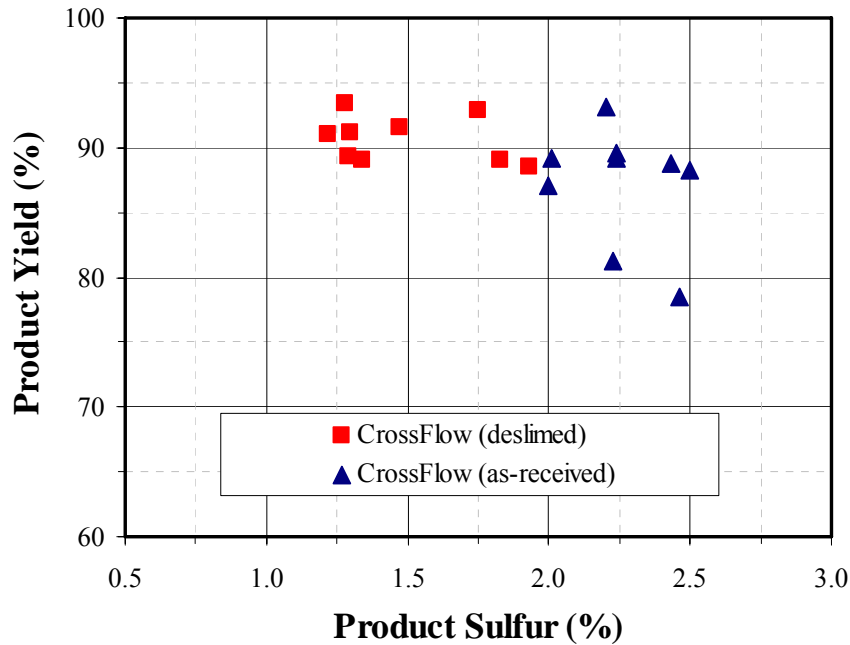


Figure 3.14. Mass yield vs. product sulfur content of +100 mesh coal at Coal Plant D.

and recovery curve. Specifically, the CrossFlow separator is capable of producing a product ranging between 6% and 11% ash at a combustible recovery of greater than 97% (when deslimed at 100 mesh). At maximum separation efficiency, the combustible recovery, for this application, approached 98%. The data presented in Figure 3.14 indicates that the sulfur content of the corresponding product will be approximately 1.50%. Table 3.13 is a summary of test results of the “x 100 Mesh” material for all nine tests conducted during this series.

The material balance outlined in Figure 3.15 is included as a summary of the test work conducted at the Coal Plant D. This material balance includes all expected metallurgical results, ancillary requirements, and volumetric flows for a full-scale installation with the capacity to treat 175 tph of feed at approximately 50% solids, by weight. A 9x9-ft CrossFlow separator has been recommended for the circuit, offering 81 ft² of cross-sectional area which results in a normalized feed rate of 2.1 tph/ft². The current test work has demonstrated the ability of the CrossFlow

Table 3.13. Test results for +100 mesh coal at Coal Plant D.

Test No.	Feed Rate (tph)	Ash (%)	Yield (%)	Comb. Recovery (%)	Ash Rejection (%)
1	1.83	9.08	88.99	97.92	53.48
2	1.95	11.35	91.20	98.49	42.20
3	2.00	9.96	92.92	98.79	39.55
4	1.73	8.67	91.60	98.52	47.37
5	2.22	5.95	91.05	98.52	58.58
6	1.84	7.59	89.26	98.13	57.50
7	2.00	10.32	93.37	98.97	37.39
8	1.93	9.66	89.10	97.87	51.51
9	1.89	8.82	88.50	97.47	54.64

separator to handle this entire flow in a single-stage circuit. After successful completion of testing at Coal Plant D, the participating company agreed to install a prototype of the CrossFlow technology at one of their processing facilities.

3.1.5 Testing at Coal Plant E

The last set of field tests with the CrossFlow unit were conducted at Coal Plant E. This effort involved equipment setup, shakedown and detailed testing. The goal of this effort was to determine the anticipated product yield and grade, combustible recovery, and feed capacity of the unit for comparison against the existing clean coal effluent cyclones at the plant. The plant personnel desired to classify minus 28 mesh clean coal slurry into plus 100 mesh and minus 100 mesh fractions. Individuals from Virginia Tech participated in the testing at Coal Plant E with cooperation from key personnel at the preparation plant.

The 9x16 inch CrossFlow separator was transported from the Coal and Minerals Research Lab at Virginia Tech in Blacksburg, Virginia to the preparation plant. With cooperation from the operators and mechanics at the plant, the separator was installed at the plant (Figure

CROSSFLOW CIRCUIT - MATERIAL BALANCE

175.0 stph Option

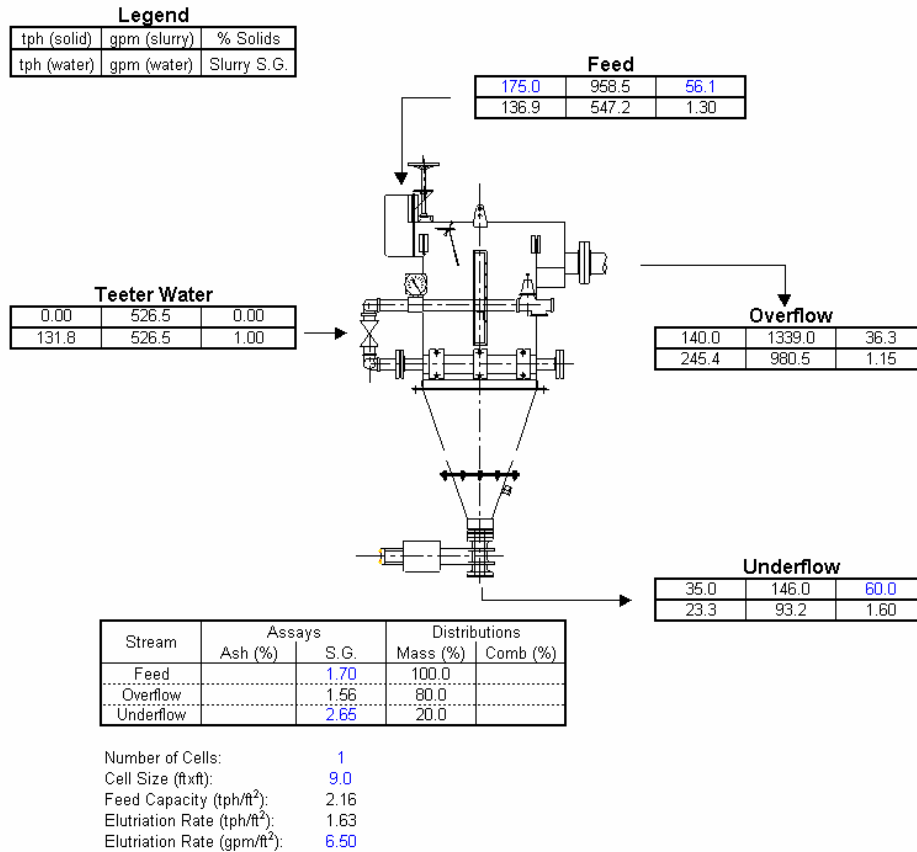


Figure 3.15. Material balance for a CrossFlow separator treating 175 tph.

3.16). Feed was supplied to the separator through a 2 inch line by connecting to a sampling port located on the feed manifold for the existing clean coal effluent cyclones. Underflow and overflow material was discharged to sizing screens in the plant, located on a level below the unit.

Plant compressed air and 115 volt electrical power were connected to the separator for the automated control system. The separator was automatically controlled through the use of a simple PID control loop which includes a pressure sensor mounted on the side of the separator to measure the relative pressure (level), a single loop PID controller, and a pneumatic pinch valve



Figure 3.16. The 9x16-inch pilot-scale CrossFlow circuit at Coal Plant E.

to control the underflow discharge to maintain a constant bed pressure (level). Clarified water was connected to the separator to create the fluidized teeter bed of solids.

After completing the installation of the test unit, preliminary shakedown testing was conducted to resolve any unexpected operational problems that could arise. These tests were normally necessary to resolve any problems that may have been overlooked in the initial engineering and to confirm that feed capabilities, pipe sizes, electrical supplies, control systems, etc., were adequate. In addition, the shakedown tests provided an opportunity to roughly determine the ranges of operating conditions that would be most appropriate for this particular application.

Two series of detailed test programs were conducted using the pilot-scale test unit. The first series of tests were performed to investigate the effects of the key design variables on separator performance and to simultaneously define the overall grade and recovery curve. The subsequent series of testing was used to investigate the effects of key operating parameters. Tests were conducted primarily as a function of teeter bed pressure and fluidization water rate. The coal/rock interface, or teeter bed, was adjusted to different levels (i.e. different bed pressure) for each steady-state test. Fluidization water was adjusted to fine tune the separation. For each test, samples were taken from the feed, overflow, and underflow streams after conditions were stabilized. Five test runs were completed during the on-site test work.

Due to the low percent solids, the fine size distribution, and the low specific gravity of the material, bed development in the CrossFlow separator was very difficult for this particular application. Initial plans to feed the unit at 1 tph/ft² could not be obtained due to the turbulence occurring in the bed formation area. Feed rates were slowly reduced over time until a 0.10 tph/ft² feed rate with a water addition rate of 1.5 gpm produced a stable bed in the unit. Even at this low feed rate, an appreciable amount of plus 100 mesh material was still reporting to the overflow. Five sets of samples were collected of the feed, overflow, and underflow streams. However, laboratory analyses were not conducted on these samples because visual observations of the product streams indicated poor performance at attempting to classify the feed stream.

The coal slurry evaluated in this series of experiments possessed a mean particle size of 0.075 mm. Table 3.14 is a summary of the array of operating parameters that were investigated during testing. The feed slurry specific gravity was measured to be 1.05 with an average of 12% solids. The feed rate was varied from 0.02-0.09 tph/ft². Due to the poor separation performance, the classification of very fine coal slurry using the CrossFlow is not recommended for this site.

Table 3.14. Operating Parameters for On-Site Pilot Scale Testing at Coal Plant E.

Unit Operation	Test Number	% Solids	Feed tph	gpm	Bed Level	Water Gpm
CrossFlow	F1	12	0.09	2.8	80	4.0
CrossFlow	F2	12	0.09	2.8	80	4.0
CrossFlow	F3	12	0.05	1.6	80	3.0
CrossFlow	F4	12	0.04	1.2	80	1.5
CrossFlow	F5	12	0.02	0.5	80	1.5

3.1.6 Discussion of Coal Plant Results

A comprehensive study of the CrossFlow separator was conducted at four coal preparation plants located in the eastern United States. In-plant testing of a 9 x 16 inch unit resulted in separation efficiencies at or above existing classification equipment in the size class of 0.2 to 1.0 mm. The data demonstrated that for any given product ash content or sulfur content, the CrossFlow separator produced a higher clean coal yield and higher combustible recoveries at higher feed rates when compared to the existing coal spirals. The CrossFlow also demonstrated its ability to handle the entire flow of multiple spirals in a single-stage circuit. For the case where the ultimate goal was to compare results against the existing clean coal effluent cyclones (28 mesh by zero material at 100 mesh), it was determined that the material was too fine to develop the necessary teeter-bed, and the project was therefore abandoned. On the other hand, the test work conducted in this series of tests supports the replacement of spirals with the CrossFlow technology for several applications. As a result, one of the coal mining companies participating in this project agreed to purchase a prototype separator for evaluation under Phase II.

3.2 Phase I Testing of Phosphate Plants

3.2.1 Testing at Phosphate Plant A

The Phase I field-testing of the HydroFloat separator involved equipment setup, shakedown and detailed testing at the Phosphate Plant A. The goal of this effort was to compare the unit to existing conventional cells in several different areas of the plant by analyzing the anticipated product grade and recovery, insol content, reagent consumption, and feed capacity at, and above, design feed rates of the unit. The three areas of the plant where the HydroFloat separator was tested included the fine feed, amine flotation and coarse feed circuits.

The main objective of the fine and coarse phosphate testing was to demonstrate the potential of the unit as a candidate for the process equipment in a proposed plant design with both fine and coarse circuits. The main objective of the amine flotation testing was to demonstrate the feasibility of using the unit for silica flotation and to develop data to determine its potential application for use in the amine flotation circuit at Phosphate Plant A. Approximately 6 months was allocated to this task.

Individuals from Eriez Manufacturing and Virginia Tech participated in the testing at Phosphate Plant A with cooperation from key personnel at the processing plant. Additional tests were conducted by Phosphate Plant A representatives to expand the data base for evaluating the potential of incorporating the HydroFloat separator into proposed circuit upgrades.

Preliminary shakedown testing was conducted after completing the installation of the test HydroFloat unit to resolve any unexpected operational problems that could arise. These tests are normally necessary to resolve any problems that may have been overlooked in the initial engineering and to confirm that feed capabilities, pipe sizes, electrical supplies, control systems, etc., are adequate. An average of six shakedown tests per circuit was conducted with the unit.

Two series of detailed test programs were conducted using the pilot-scale test unit. The first series of test were performed to investigate the effects of the key design variables on separator performance and to simultaneously define the overall grade and recovery curve.

The HydroFloat separator is designed for feed rates of 2 tph/ft² and 1 tph/ft² rougher concentrate, which allows the test unit to operate at 4 tph feed and 2 tph concentrate, respectively. The initial testing in the fine and coarse circuit evaluated the unit at loading rates much higher than design to establish the recovery fall-off. The design rates for the amine flotation circuit were not precisely known going into the testing, but were thought to be similar to those for rougher flotation. Part of the amine testing program was devoted to determining the design rates and evaluating the HydroFloat separator performance across the board, both at the design rate and above.

With the *recovery fall-off* determined for each circuit and unit configuration, the subsequent series of testing was used to investigate the effects of key operating parameters. Tests were conducted to establish reagent consumption (fatty acid, surfactant, amine and diesel oil), to investigate the bed levels and sparger water required for the best unit operation and to investigate the variability associated with the overall system. For each test, samples were taken from the feed, concentrate and tailings streams after conditions were stabilized. The samples were analyzed for BPL, MgO and insol contents. All as-received results were analyzed and adjusted using mass balance software to ensure the test data was reliable and self-consistent. Any experimental values that were deemed by the mass balance routines to be unreliable were removed from the data set. The participating mining company used the compiled data to establish the metallurgical improvement, operating savings and economic payback that may be realized by implementing the proposed high-efficiency technologies.

The process evaluation has been divided into three sections including (i) fine feed circuit, (ii) amine flotation circuit, and (iii) the coarse feed circuit.

a) Testing at Phosphate Plant A - Fine Circuit

The installation of the pilot-scale unit in the fine feed circuit at Phosphate Plant A was the main objective of this task. The separator was transported from the Eriez Manufacturing Central Research Lab in Erie, Pennsylvania to the processing plant. With cooperation from the operators and mechanics at the plant, the 18-inch diameter pilot-scale HydroFloat separator was installed at the fine circuit at Phosphate Plant A as shown in Figure 3.17. Reagentized feed was supplied to the HydroFloat separator through a 2 inch line connected to the existing plant conditioning tanks.



Figure 3.17. The 18-inch diameter pilot-scale HydroFloat circuit at Phosphate Plant A.

Concentrate and tailings streams were discharged into floor sumps.

The unit was operated as a column flotation cell, utilizing the HydroFloat separator air sparging system. The test unit included three compartments that allowed more water and air to be added (up to 60 gpm water and 10 cfm air). There was no teeter-bed required in this system. Plant compressed air and 115 volt electrical power were connected to the separator for the automated control system. The separator was automatically controlled through the use of a simple PID control loop which includes a pressure sensor mounted on the side of the separator to measure the relative pressure (level), a single loop PID controller, and a pneumatic pinch valve to control the underflow discharge to maintain a constant bed pressure (level).

Fifty-three tests were conducted during the fine circuit testing at Phosphate Plant A. Testing in the fine circuit produced an average of 10% higher BPL recoveries with a 0.8% lower BPL rougher tail in the HydroFloat separator than in the plant Wemco cells. Figure 3.18 displays

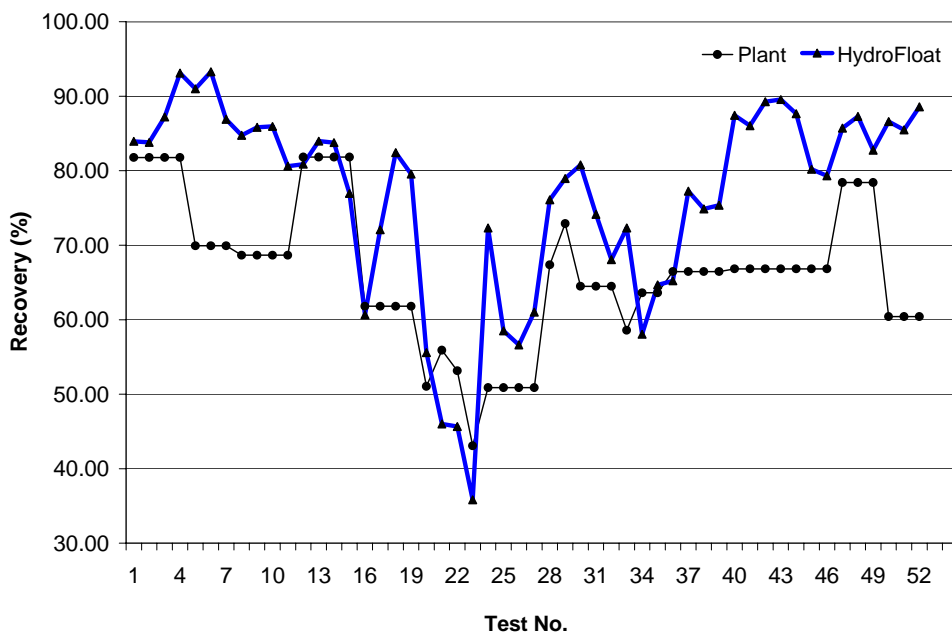


Figure 3.18. Comparison of recovery at Phosphate Plant A (Fine Circuit).

the HydroFloat separator and plant tails percent BPL for each test. The plant Wemco cells averaged only about 0.7% BPL higher-grade rougher concentrates than the HydroFloat as shown in Figure 3.19. An average HydroFloat separator rougher concentrate grade of 54.9% BPL is satisfactory considering the test feed grade only average 8% BPL through most of the testing.

During testing, several attempts were made to obtain final grade concentrates (7% insol) with one stage of flotation. The results show that insol concentrates between 9-10% produced only 74-76% recoveries, and dropping the insol to 7-8% reduced recoveries to 70% or less. Further testing in this area needs to be conducted utilizing more selective reagents or higher feed grades to achieve the desired 7% insol concentrates in a one step flotation process with the HydroFloat separator.

One of the most important operating parameter to consider for fine flotation is the ability

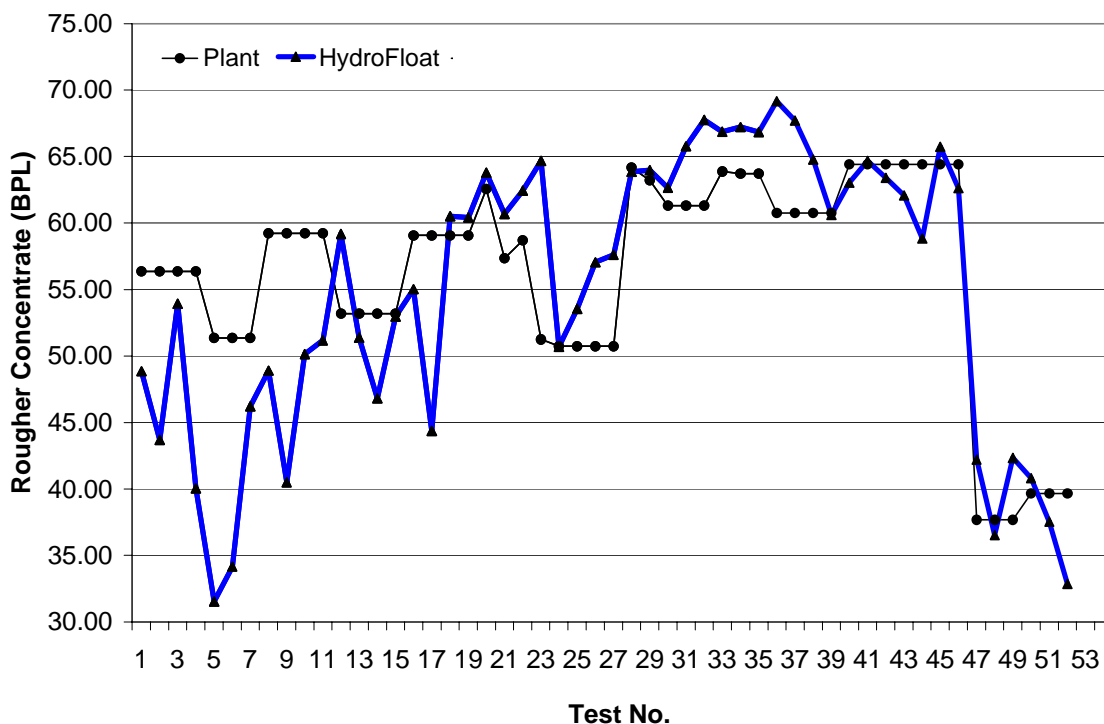


Figure 3.19. Comparison of rougher BPL grade at Phosphate Plant A (Fine Circuit).

of the process equipment to recover coarser material into an acceptable concentrate: i.e., recover coarse phosphate without recovering fine silica. Comparison testing of the HydroFloat separator with the Wemco Cell produced promising results. As shown in Figure 3.20, the HydroFloat separator recovered 80%, 83%, and 88% of the plus 20 mesh, 20 x 28 mesh, and 28 x 35 mesh phosphate, respectively. The performance values were well above those established for the plant; the plant recovered only 24% of the plus 35 mesh and 67% of the plus 48 mesh phosphate.

Percent solids in the tailings averaged between 20-30% at optimum testing conditions. During less than optimum conditions, the solids were as high as 53%. Optimum conditions occurred at 70-75 bed levels, with between 50-60 gpm of sparger water, and 4 tph feed. While higher bed levels and less sparger water could produce a slightly higher percent solids in the tailings, this adversely affected the recovery and concentrate grades. Using the unit with three compartments and with bed levels of 70-75, the optimum froth depths were 15-20 inches.

Reagent dosages were affected by the poor water quality and excessive slimes in the feed

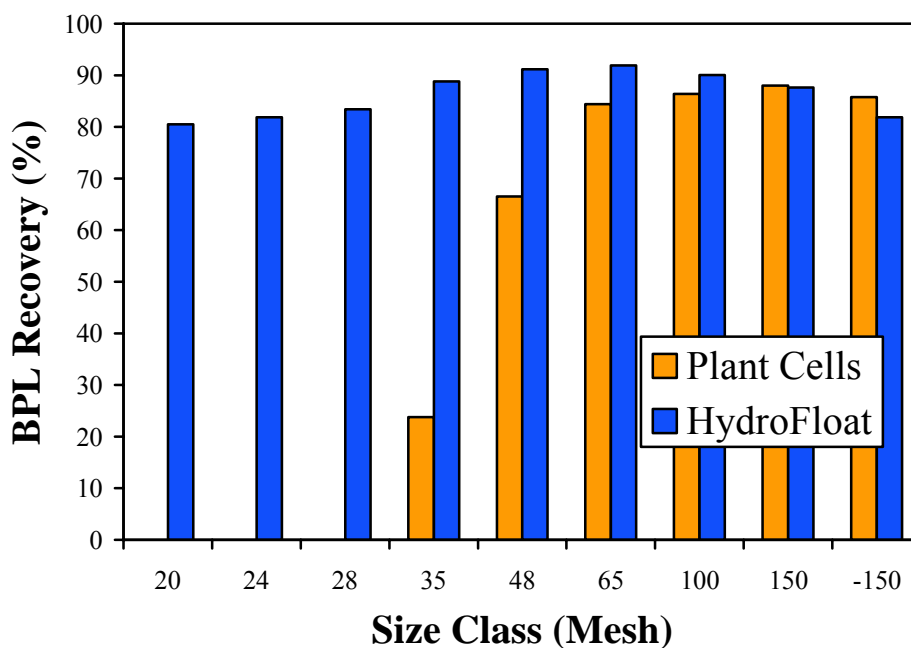


Figure 3.20. Fine phosphate results at Phosphate Plant A (Plant Circuit #2).

during the testing program. The fatty acid dosage in the plant ranged from 0.80 to 1.20 lb per ton of fine feed during testing, whereas the fuel oil dosage in the plant ranged from 0.35 to 0.55 lb per ton fine feed. The fuel oil dosage was slightly higher than average dosage at Phosphate Plant A, which is partially to blame for the poorer than expected recoveries.

The recommended surfactant dosage was 0.13 lb per ton at design rates, with actual results being slightly higher. Dosage in the HydroFloat ranged from 0.20 to 0.32 lb per ton of feed (6.9 to 10.4 cc per minute). Projected surfactant dosage for the fine circuit can not be determined, but it is estimated that it is just slightly higher than the recommended dosage.

While the operation of the HydroFloat separator for fine flotation was difficult to optimize due to various outside variables affecting the system, a significant number of tests were conducted at differing operating variables under varying operating conditions to achieve optimum operating conditions. The optimum conditions for the HydroFloat separator for use in fine flotation as defined by this testing program are: three compartment unit, with bed level between 70-75, a froth depth of 15-20 inches, sparger water between 55-60 gpm, air flow of 10 cfm, and a surfactant dosage of at least 0.2 lb per ton of feed. The measured recovery values and concentrate grade at these design rates were acceptable. Based on this data, the HydroFloat separator can successfully be implemented into the Phosphate Plant A fine flotation circuit.

b) Testing at Phosphate Plant A - Amine Circuit

The same separator used in the fine circuit was also used in the amine flotation circuit. With cooperation from the operators and mechanics at the plant, the 18-inch diameter pilot-scale HydroFloat separator was installed in the amine circuit at Phosphate Plant A. Reagentized feed

was supplied to the HydroFloat separator through a two-inch line connected to the existing plant conditioning tanks. Concentrate and tailings streams were discharged into floor sumps.

The unit was operated as a column flotation cell, utilizing the HydroFloat separator air sparging system. The test unit included three compartments that allowed more water and air to be added (up to 60 gpm water and 10 cfm air). There was no teeter-bed required in this system. Plant compressed air and 115 volt electrical power were connected to the separator for the automated control system. The separator was automatically controlled through the use of a simple PID control loop which includes a pressure sensor mounted on the side of the separator to measure the relative pressure (level), a single loop PID controller, and a pneumatic pinch valve to control the underflow discharge to maintain a constant pressure (level).

Twenty-four tests were conducted during the amine flotation circuit testing at Phosphate Plant A. HydroFloat separator testing in the amine flotation circuit produced an average of 1.3% higher insol concentrate and recovered about 8% less insol to the amine tailings than in the Plant Wemco Cell. Figure 3.21 displays the concentrate grade for the HydroFloat separator and the plant for each test. The plant Wemco cells averaged only about 0.5% higher BPL recovery than the HydroFloat separator as shown in Figure 3.22.

The HydroFloat separator performed virtually the same as the plant Wemco cell for amine flotation over the range 3 to 18% concentrate insol and 95 to 99% BPL concentrate recovery. The unit demonstrated it could effectively recover coarse silica. The HydroFloat separator insol recovery values were about 3% lower on average than those in the plant at above design feed rates. The differences ranged from 6% to 11% in the 35 mesh and 48 mesh fractions to 2% in the finer fractions. The HydroFloat separator insol recovery values were about 2% higher on average than those in the plant at the lower feed rates.

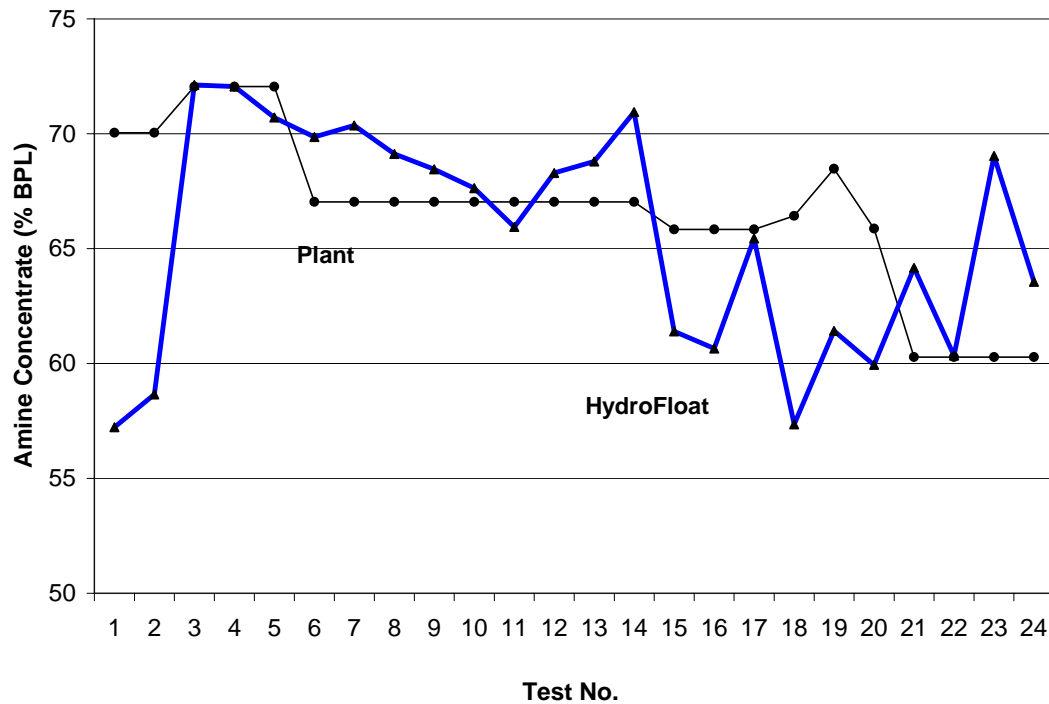


Figure 3.21. Comparison of concentrate grade at Phosphate Plant A (Amine Circuit).

One of the most important operating parameters to consider for amine flotation is the ability of the process equipment to recover coarse silica without recovering phosphate. Comparison testing of the HydroFloat separator with the Wemco Cell produced promising results. As shown in Figure 3.23, the HydroFloat separator had just slightly less recoveries than the plant for all of the size fractions except the 35 mesh, where it had a nearly 6% increase in BPL recovery than the plant.

Reagent dosages were affected by the poor water quality and excessive slimes in the feed during the testing program. The surfactant dosage for the HydroFloat separator ranged from 0.13 to 0.40 lb per ton of feed. The recommended dosage was 0.14 lb per ton at design rates.

The interactions of varying diesel fuel dosage rates were studied during the amine circuit testing. Amine flotation circuits use diesel oil or polymer occasionally to modify the froth when

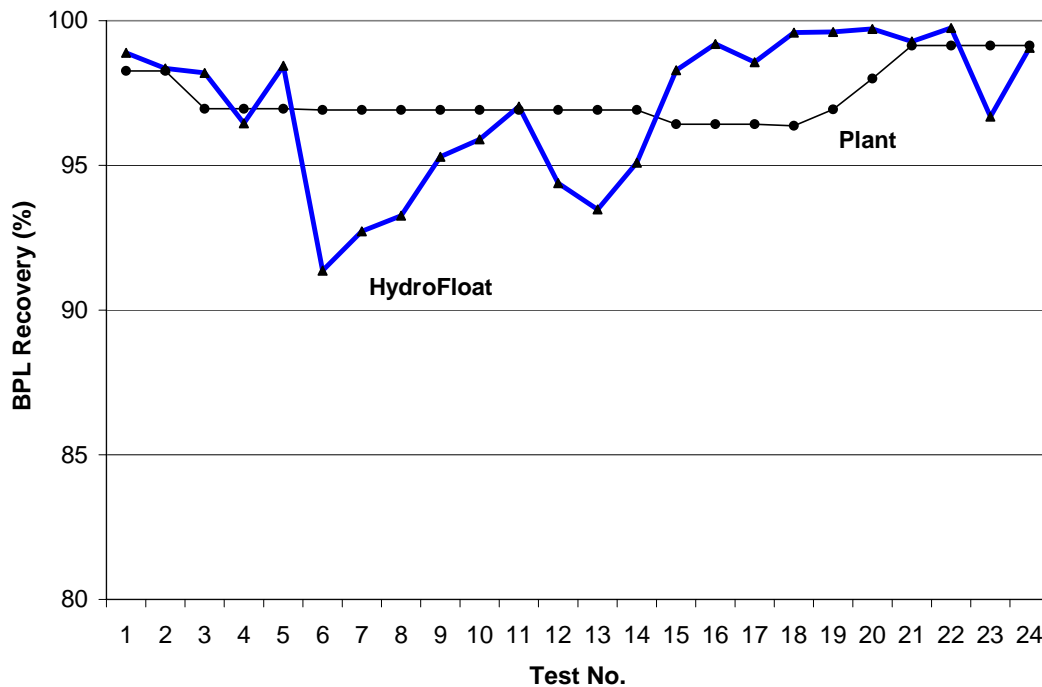


Figure 3.22. Comparison of BPL recovery at Phosphate Plant A (Amine Circuit).

slimy water is present. Froth stability was investigated, but was difficult to determine due to the lack of air flow measurement available at the time of testing. Exact diesel fuel dosage rates are unknown at this time.

While the operation of the HydroFloat separator for amine flotation was difficult to optimize due to various outside variables affecting the system, a significant number of tests were conducted at differing operating variables under varying operating conditions to achieve optimum operating conditions. The optimum conditions for the HydroFloat separator for use in amine flotation as defined by this testing program are: three compartment sections, with bed level between 70-75, a froth depth of 15-20 inches, sparger water at 25 gpm, air flow of 10 cfm, and a surfactant dosage of at least 0.2 lb per ton of feed. Additional testing will be needed in the future to validate these recommendations. The measured silica recovery values and concentrate

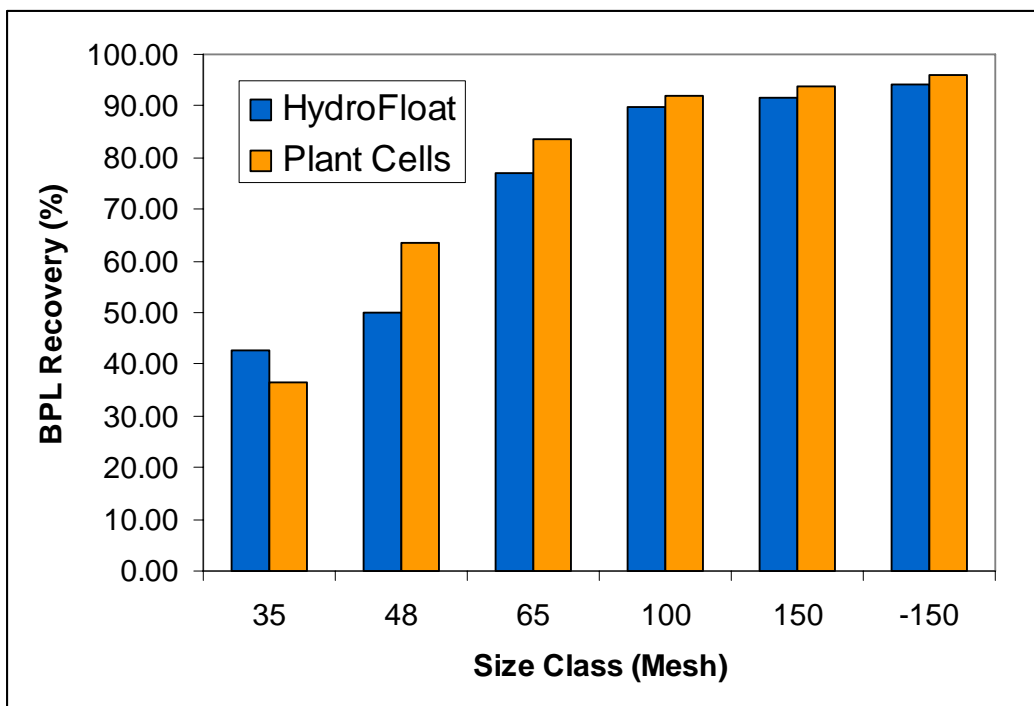


Figure 3.23. Comparison of test results for amine phosphate (Plant Circuit #2).

grades at these design rates were acceptable. Based on this data, the HydroFloat separator can successfully be implemented into the Phosphate Plant A amine flotation circuit.

c) Testing at Phosphate Plant A - Coarse Circuit

The same separator used in the fine and amine flotation circuits was also used in the coarse circuit, with one modification. The center compartment was removed from the unit, so as to allow the unit to operate with a typical teeter-bed (a total of two compartments). With cooperation from the operators and mechanics at the plant, the 18-inch diameter pilot-scale HydroFloat separator was installed in the coarse circuit at Phosphate Plant A. Reagentized feed was supplied to the HydroFloat through a 2-inch line connected to existing plant conditioning tanks. Concentrate and tailings streams were discharged into floor sumps.

Electrical power at 115 volt and plant compressed air were connected to the separator for the automated control system. The separator was automatically controlled through the use of a simple PID control loop which includes a single loop PID controller, a pressure sensor mounted on the side of the separator to measure the relative pressure, and a pneumatic pinch valve to control the underflow discharge to maintain a constant bed pressure.

Twenty-four tests were conducted during the coarse circuit testing at Phosphate Plant A. Testing in the coarse circuit produced an average 12% higher BPL recovery with a 3.5% lower BPL rougher tail in the HydroFloat separator than in the Plant Wemco Cell. Figure 3.24 displays the HydroFloat separator and plant tails percent BPL for each test. Figure 3.25 displays the concentrate recovery for the HydroFloat separator and Plant Wemco Cell. The plant average about 6% BPL higher-grade rougher concentrates than the HydroFloat separator as shown in Figure 3.26. However, the average concentrate grade of 62.6% BPL was still considered

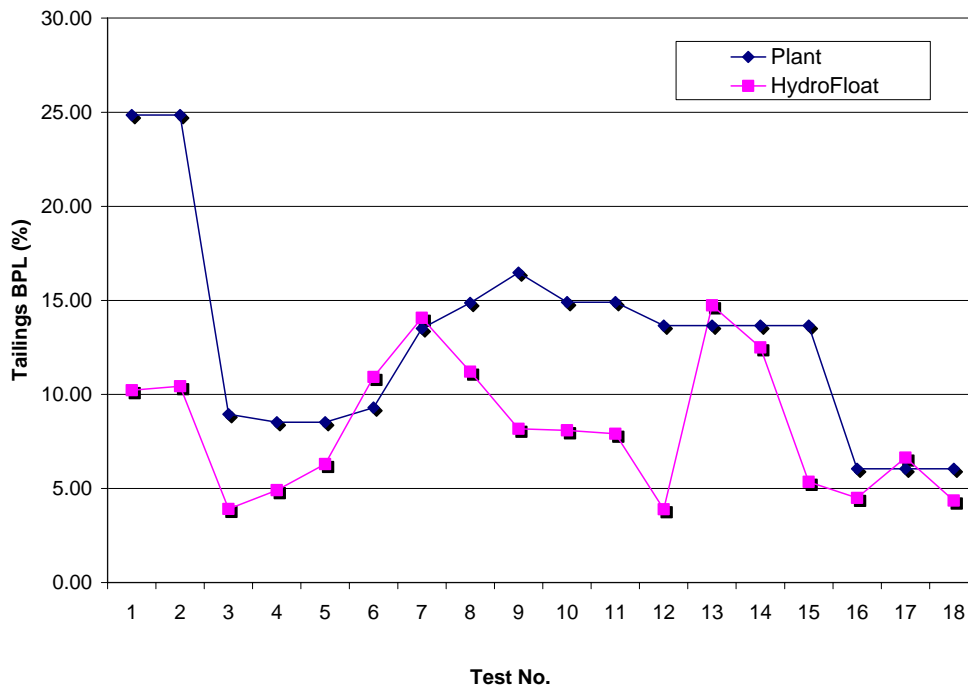


Figure 3.24. Comparison of tailings grade at Phosphate Plant A (Coarse Circuit).

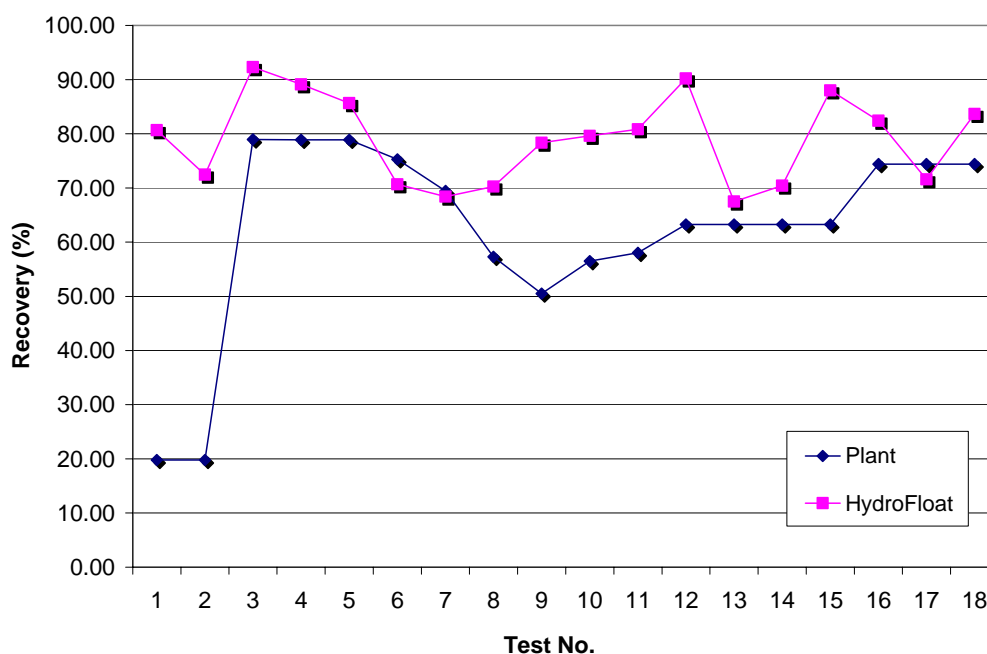


Figure 3.25. Comparison of recovery at Phosphate Plant A (Coarse Circuit).

satisfactory for the testing.

As with the fine and amine flotation circuits testing, poor water quality played an important role in the overall performance of the reagents during testing. Fatty acid dosage in the plant ranged from 2.04 to 3.61 lb per ton of coarse feed during testing, while fuel oil dosage ranged from 1.06 to 1.68 lb per ton of feed. Both of these values are considered high for Phosphate Plant A, and hindered recoveries as a result.

Surfactant dosage for the HydroFloat ranged from 0.23 to 0.77 lb per ton of feed, which was also considered to be a high dosage, mostly attributable to the high fatty acid-fuel oil dosage in the plant. Other contributing factors were the poor water quality and the need to set the surfactant dosage rates higher than normal in the plant to maintain an adequate froth bed depth. This was the case in the fine and amine flotation circuits testing as well.

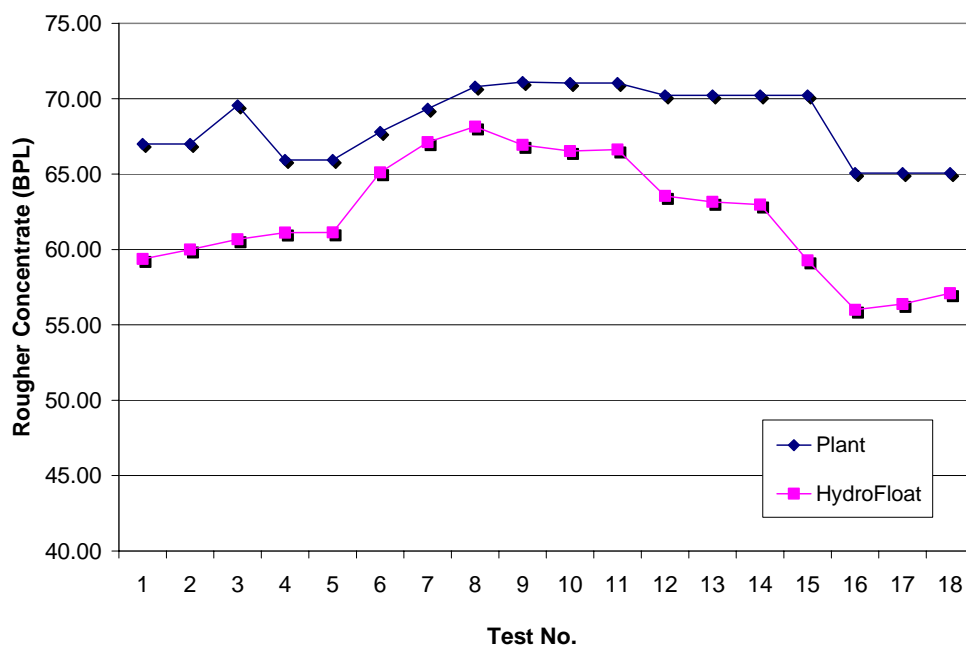


Figure 3.26. Comparison of BPL grade at Phosphate Plant A (Coarse Circuit).

The ability of the unit to recover coarse material into an acceptable concentrate proved to be successful during the testing program. One test achieved an overall BPL of 92% at a feed rate of 3.92 tph (98% of design) and a concentrate overflow froth rate of 1.56 tph (78% of design). The associated concentrate grade was 61% BPL. Screen and chemical analyses were conducted on selected tests to determine the recovery values for various mesh sizes. The HydroFloat separator recovery values are considered to be excellent as shown in Figure 3.27.

Percent solids in the tailings averaged 75.8% for all tests. The HydroFloat separator was configured with two compartments, with bed levels between 82 and 87, and with a recommended level of 85. This resulted in optimum condition of: froth depths between 15 and 20 inches, sparger water near 20 gpm, and air flow at 5.0 cfm. The measured recovery values and concentrate grade at these design rates were acceptable. Based on this test data, the HydroFloat

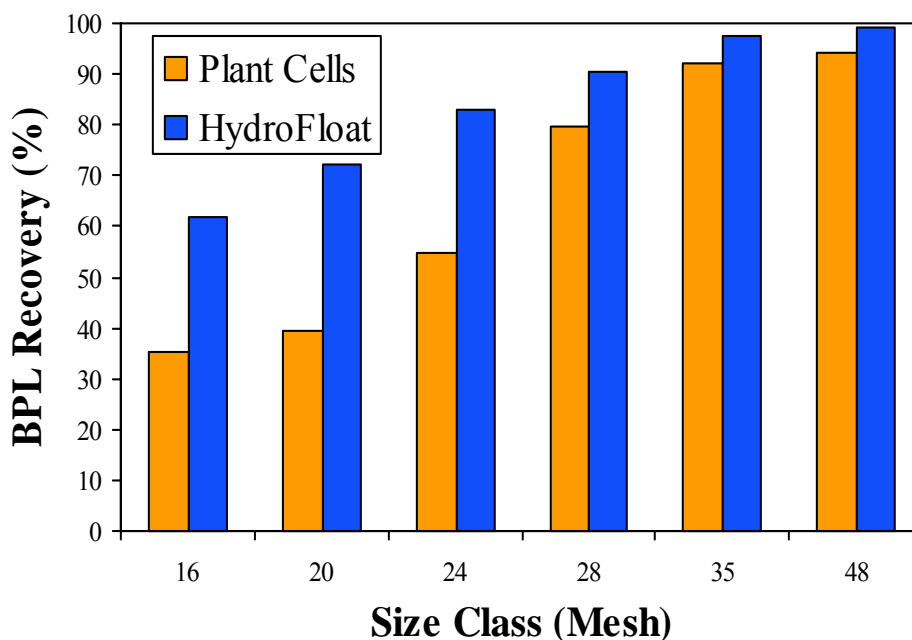


Figure 3.27. Comparison of test results for coarse phosphate (Plant Circuit #1).

can successfully be implemented into the Phosphate Plant A coarse flotation circuit with a relatively high degree of confidence that the unit will perform exceptionally well.

3.2.2 Testing at Phosphate Plant B

Equipment setup, shakedown testing, and detailed testing comprised the phase I field-testing of the HydroFloat separator at Phosphate Plant B. The goal of this effort was to compare the unit to existing hydroclassifiers and conventional cells by analyzing the anticipated product grade and recovery, insol content, reagent consumption and feed capacity at, and above, design feed rates of the unit. The main objective of testing was to determine if the HydroFloat separator could achieve higher recoveries of the ultra-coarse particles than the existing second-stage hydroclassifier at the plant. Further investigations of the coarse and fine matrices were conducted, comparing results against the existing conventional cells currently in operation at the plant.

Approximately 12 months was allocated to this task. Individuals from Eriez Manufacturing and Virginia Tech participated in the testing at Phosphate Plant B with cooperation from key personnel at the processing plant.

The separator was transported from the Eriez Manufacturing Central Research Lab in Erie, PA to the processing plant. With cooperation from the operators and mechanics at the plant, the 1-foot diameter pilot-scale HydroFloat separator was installed at each circuit (ultra-coarse, coarse and fine) for a period of several weeks for each circuit at Phosphate Plant B as shown in Figure 3.28. Reagentized feed was supplied to the HydroFloat separator through a 2-inch line connected to the existing plant conditioning tanks. Concentrate and tailings streams were discharged into floor sumps. Plant compressed air and 115 volt electrical power were connected



Figure 3.28. Pilot-scale HydroFloat circuit at Phosphate Plant B.

to the separator for the automated control system. The separator was automatically controlled through the use of a simple PID control loop which includes a pressure sensor mounted on the side of the separator to measure the relative pressure (level), a single loop PID controller, and a pneumatic pinch valve to control the underflow discharge to maintain a constant bed pressure (level). Clarified water was connected to the separator to create the fluidized teeter bed of solids.

After completing the installation of the test HydroFloat unit in each circuit, preliminary shakedown testing was conducted to resolve any unexpected operational problems that could arise. Shakedown test are commonly utilized to resolve any problems that may have been overlooked in the initial engineering and to confirm that feed capabilities, pipe sizes, electrical supplies, control systems, etc., are adequate.

Two series of detailed test programs were conducted for each circuit using the pilot-scale test unit. The first series of test were performed to investigate the effects of the key design variables on separator performance and to simultaneously define the overall grade and recovery curve.

The HydroFloat separator is designed for feed rates of 2 tph/sqft and 1 tph/sqft rougher concentrate, which allows the test unit to operate at 4 tph feed and 2 tph concentrate, respectively. The initial testing in the coarse circuit evaluated the unit at loading rates much higher than design, to establish the *recovery fall-off*. With the *recovery fall-off* determined for each circuit and unit configuration, the subsequent series of testing was used to investigate the effects of key operating parameters. Tests were conducted to establish reagent consumption (fatty acid, surfactant, and diesel oil), to investigate the bed levels and sparger water required for the best HydroFloat separator operation, and to investigate the variability associated with the

overall system. For each test, samples were taken from the feed, concentrate and tailings streams after conditions were stabilized. The samples were analyzed for BPL, MgO, and insol contents.

To ensure the test data was reliable and self-consistent, all as-received results were analyzed and adjusted using mass balance software. Experimental values that were deemed by the mass balance routines to be unreliable were removed from the data set. The participating mining company used the compiled data to establish the metallurgical improvement, operating savings and economic payback that may be realized by implementing the proposed high-efficiency technologies.

The process evaluation has been divided into three sections including the (i) ultra-coarse rock feed, (ii) the coarse rock feed, and (iii) the fine feed circuits.

a) Testing at Phosphate Plant B – Ultracoarse Feed

Grade versus recovery data for the in-plant evaluation of the HydroFloat had BPL recoveries of 87% to 99% with product grades ranging between 5% and 14% insols. The resulting products contained, on average, 67% BPL. Figure 3.29 is a graph of the grade versus recovery data for the in-plant testing and earlier laboratory-scale testing. Size-by-size analysis of the HydroFloat was conducted and results are presented in Figure 3.30. The HydroFloat is capable of high BPL recoveries for even the coarsest size fractions, where 96.7% of the available BPL in the +16 mesh size class was recovered.

b) Testing at Phosphate Plant B – Coarse Feed

Figure 2.16 summarizes the grade and recovery data for the coarse feed test work. BPL recoveries ranged from 90% to 98% while product grades averaged 24.7% insols. The resulting

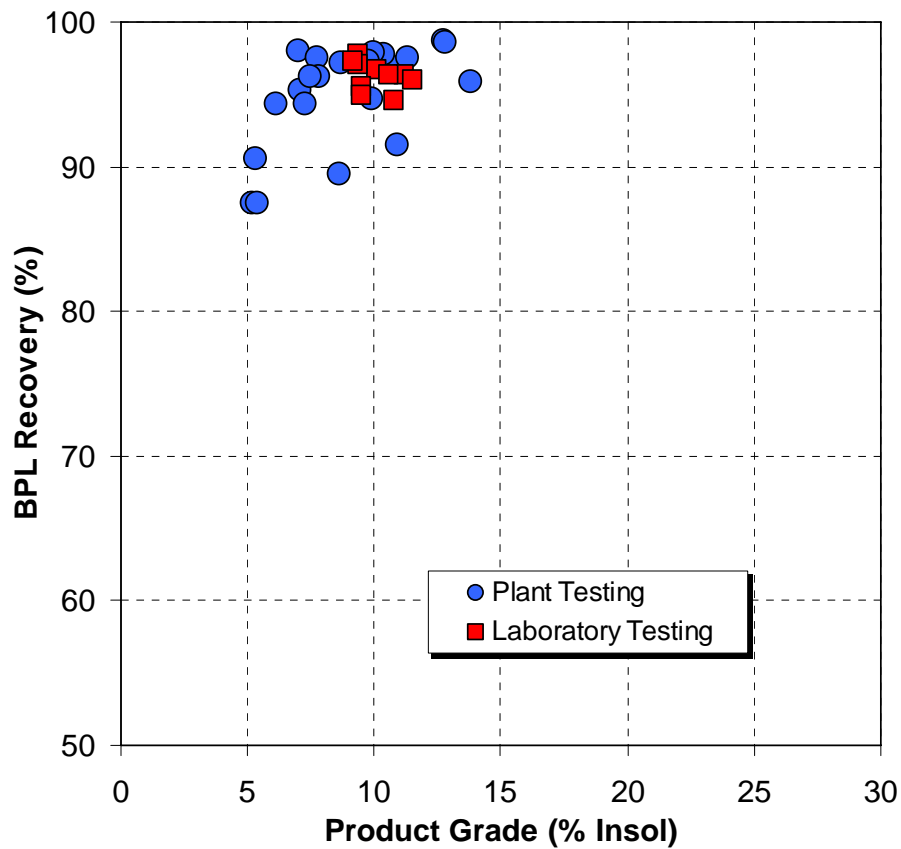


Figure 3.29. BPL recovery vs. product insol for ultra-coarse feed at Phosphate Plant B.

products contained, on average, 55% BPL by weight. Figure 3.31 also illustrates that the results for the laboratory evaluations were superior to those produced for the in-plant trials. This occurrence is a direct result of the mean particle size difference found between the samples used for the laboratory and in-plant testing. It was calculated that the sample used for the coarse matrix laboratory testing was as coarse (mean size: 0.706 mm) as the sample provided for the ultra-coarse testing (mean size: 0.721 mm). During the in-plant trials, it was observed that the coarse matrix was significantly finer, amplifying any occurrence of hydraulic carry-over or activation of fine floatable insols.

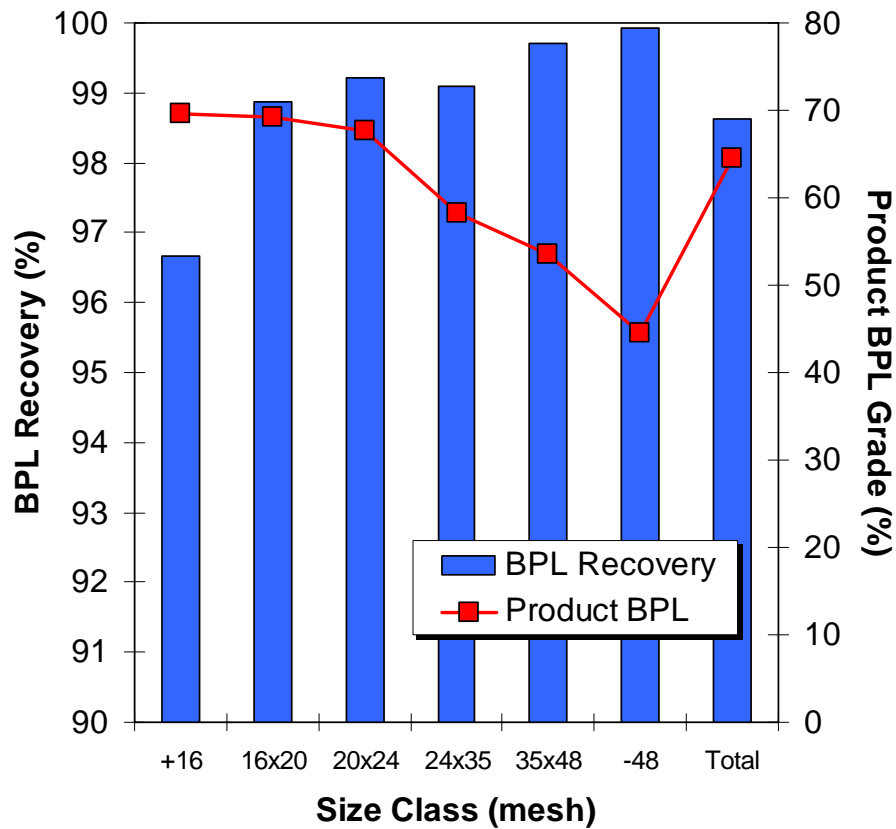


Figure 3.30. Size-by-size recovery and grade for ultracoarse feed at Phosphate Plant B.

c) Testing at Phosphate Plant B – Fine Feed

The results from the in-plant testing on the fine matrix are shown in Figure 3.32. BPL recovery ranged from 88% to 97% using the HydroFloat. When operated as an open column, BPL recoveries ranged from 85% to 92%, though at a significantly lower product insol (37% vs. 22%, respectively). Results from samples collected around the existing plant rougher-scavenger swing circuit are also presented in Figure 3.32 for comparison. The findings indicate that the open column cell (w/ HydroFloat sparging system) is able to achieve incrementally higher BPL recoveries at lower product insol grades compared to either the HydroFloat or the existing

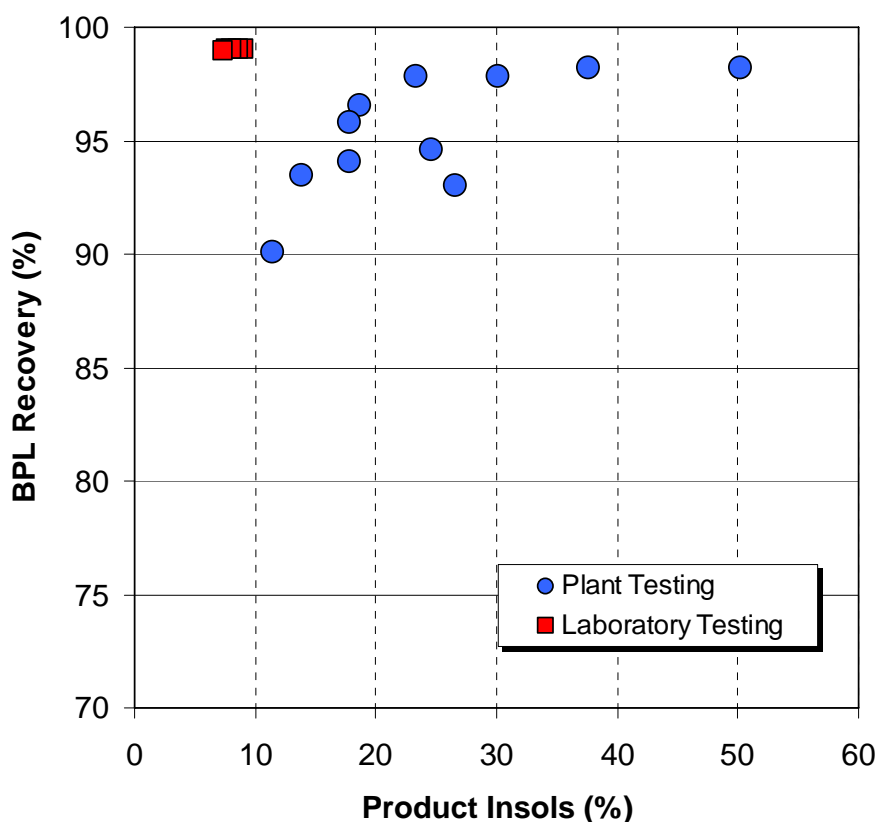


Figure 3.31. BPL recovery vs. product insol grade for coarse feed at Phosphate Plant B.

column technology. The corresponding product grade (%BPL) averaged 55% for the open column system as seen in Figure 3.33. As with the ultra-coarse and coarse circuits, the HydroFloat achieved an acceptable product grade and recovery in the fine circuit.

3.2.3 Discussion of Phosphate Plant Results

The in-plant evaluation of the HydroFloat separator demonstrated that this novel separation device can successfully treat the three different size fraction in a typical phosphate processing plant. For the ultra-coarse rock, the separator produced a high grade phosphate product (+66% BPL) at BPL recoveries exceeding 95%. For the coarse sized feed fraction, the

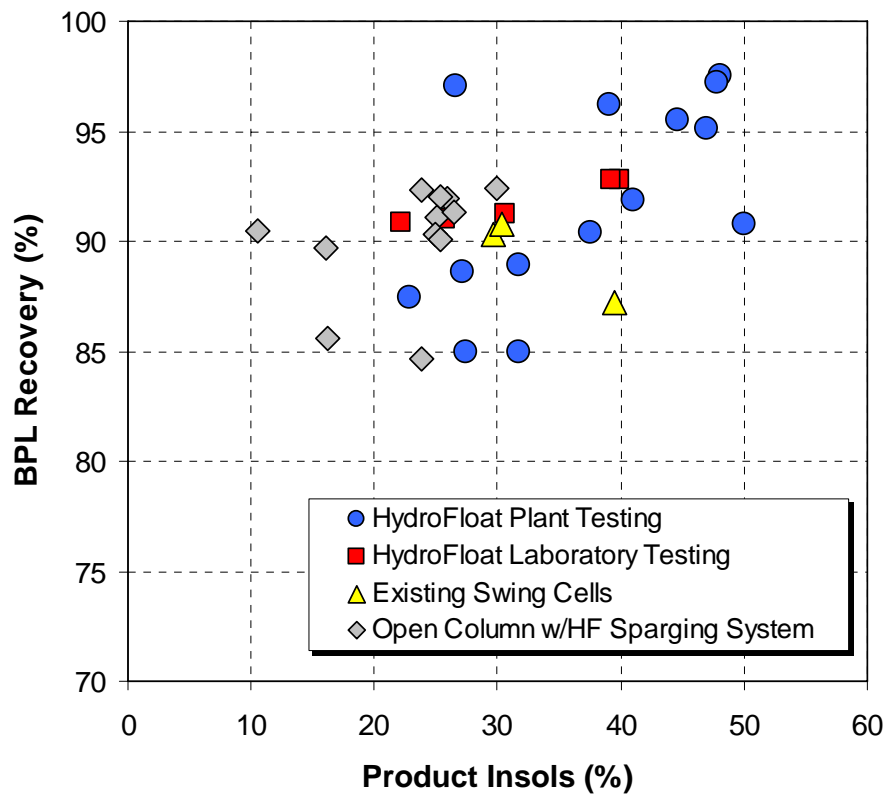


Figure 3.32. BPL recovery vs. product insol grade for fine feed at Phosphate Plant B.

separator produced a 99% BPL recovery at an 8% insol grade. Significant improvements were also achieved in the fine feed fractions where a BPL recovery greater than 90% was achieved with product insoles ranging between 22-25%.

The test data indicated that several advantages can be realized through implementation of the HydroFloat system. The system can provide a higher product mass recovery, superior metallurgical results, lower reagent costs and lower power requirements, with the greatest advantage being the higher separation efficiency. A higher product mass recovery with a better product quality is a significant achievement for this application. The HydroFloat has a substantially lower operating cost due to reduced reagent consumption and power requirements compared to conventional equipment.

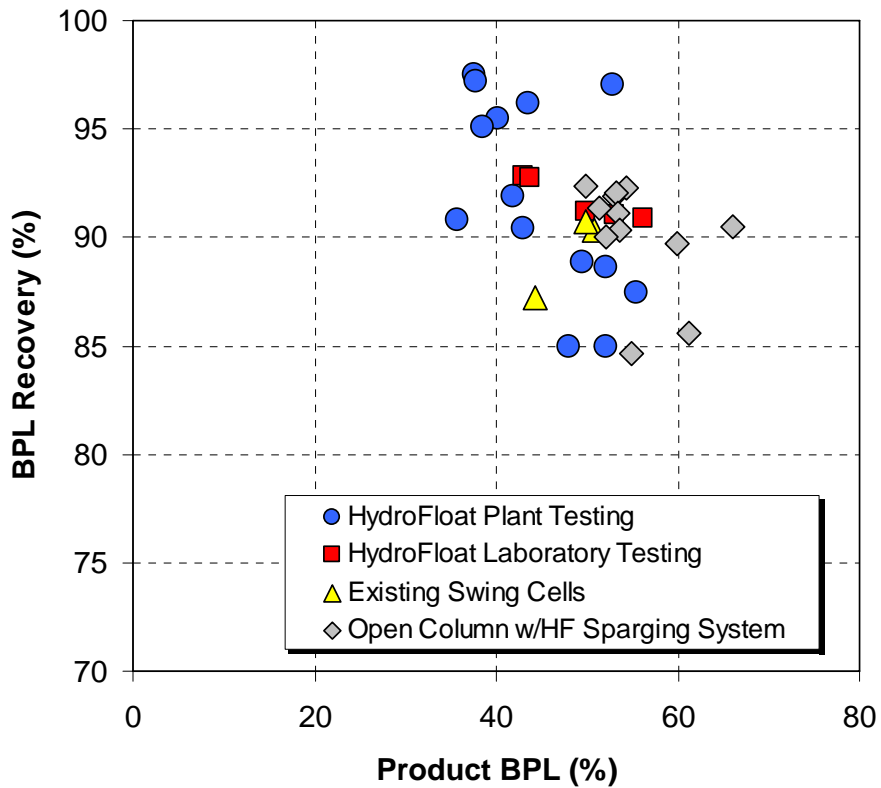


Figure 3.33. BPL recovery vs. product BPL grade for fine feed at Phosphate Plant B.

One of the goals of this project is to successfully prove the technology in a sufficient period of time to minimize the financial risk that will be taken by industry. The previous years test work has eliminated the uncertainties associated with the HydroFloat separator by proving plant scale units do in fact work. This can be seen by the fact that industry leaders have submitted purchase requests for full scale units in their preparation plants. Based on the successful installation of these full scale units, further implementation of additional units can be utilized in a broad spectrum of companies and industries.

Key design and operating variables have been established based on the performance capabilities of the HydroFloat separator. From here, proof-of-concept (POC) tests using a production-scale unit can be implemented at the various test locations where full scale prototypes

are being installed. The POC-scale tests will identify critical scale-up criteria for the design of industrial applications. The POC-scale tests will also be used to define the performance capabilities of the high-efficiency processes in an industrial setting and to fully demonstrate the potential economic benefits that can be realized with the HydroFloat separator.

Finally, it should be emphasized that the pilot-scale testing at Phosphate Plant B proved to be successful. As a result, the participating mining company agreed to purchase a prototype HydroFloat separator for testing and evaluation. The prototype unit was compared to existing flotation cells in the coarse recovery circuit under Phase II of this project. This effort is discussed in detail in the following section of this report.

4.0 RESULTS AND DISCUSSION - PHASE II

4.1 Phosphate Size Classification Using the CrossFlow Classifier

4.1.1 Pilot-Scale Test Results

An on-site test program was conducted at an industrial phosphate plant to evaluate the potential benefits of the CrossFlow separator for particle classification. The 2 x 2 ft pilot-scale unit was installed to partition the 16 x 150 mesh plant feed for the existing flotation circuits into narrowly-sized fractions. Comparison tests were also performed using a pilot-scale conventional classifier so that any improvements in sizing performance could be accurately quantified. Table 4.1 provides a summary of the operating conditions examined for each classifier. For each test, representative samples were collected from the feed, overflow, and underflow. The samples were subjected to sieve analysis and the results were mass balanced using a sum-of-least-squares method to assess the reliability of the experimental data. Data that mass balanced poorly were deemed unreliable and eliminated from the analysis.

The mass balanced data were used to construct partition curves for each test run performed for the two classifiers. Figure 4.1 shows an example of a partition curve obtained using the CrossFlow separator. The partition number represents the recovery of dry solids from the feed to the underflow (oversize) product for each size class. The partition curves were used to determine the imperfection (I) for each test. The imperfection is a dimensionless number

Table 4.1. Conditions used for the CrossFlow pilot-scale tests.

Test Variable	Conventional	CrossFlow
Feed Rate (tph/ft ²)	2-9	1-7
Feed Solids (%)	15-40	15-50
Water Rate (gpm)	190	40-90

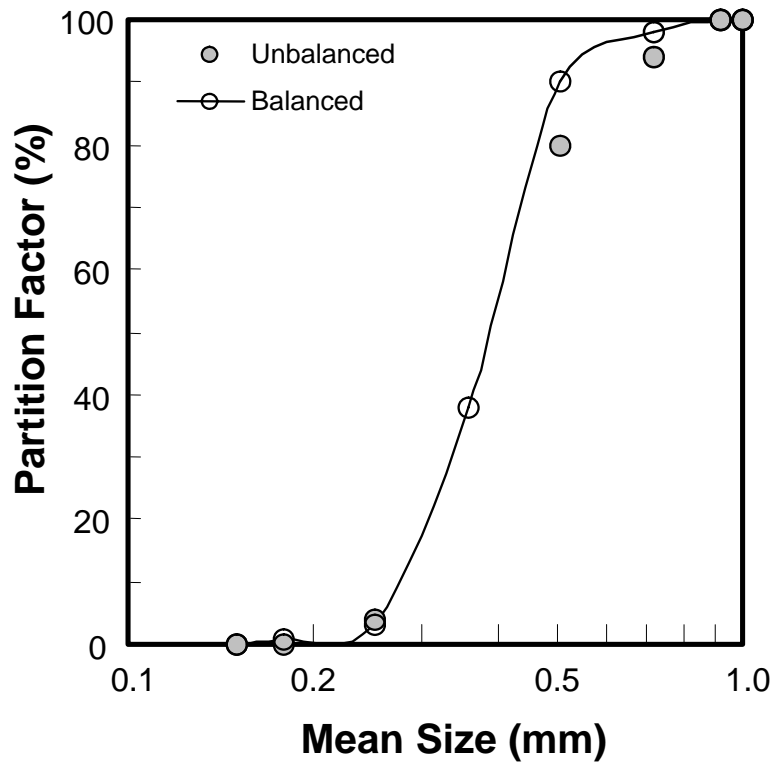


Figure 4.1. Example of a CrossFlow partition curve.

commonly used to quantify the efficiency of sizing units. A lower number represents a steeper curve and thus a better separation. A vertical line represents a perfect separation. The imperfection (I) is determined by:

$$I = (d_{75} - d_{25}) / 2d_{50} \quad [1]$$

Using this approach, the test results were analyzed to compare the performance of each separator. These results, which are compared in Figure 4.2, show the imperfection of each unit as a function of dry feed rate. The test results indicate the CrossFlow unit consistently performed at a higher level of efficiency (lower imperfection). Close examination of the test results indicated that the lower efficiency associated with the conventional classifier was due to misplacement of

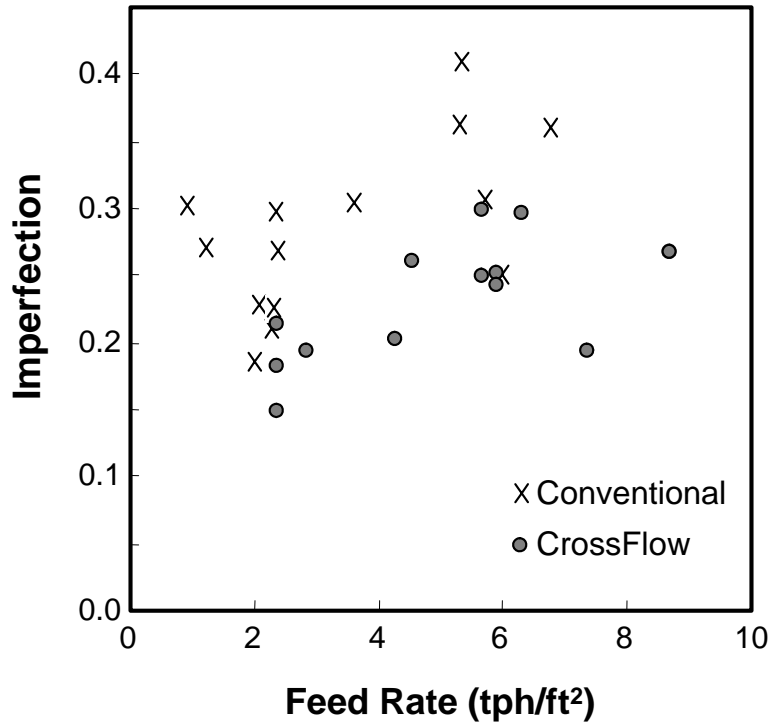


Figure 4.2. Imperfection versus superficial solids feed rate.

coarse material to the overflow product created by the higher flow rate and greater turbulence within the upper section of the conventional sizer. On the other hand, the CrossFlow hindered-bed separator maintained a uniform (laminar) flow pattern and thus the amount of misplaced material was minimized.

It is also important to note that the unique design of the CrossFlow makes it possible to accurately control the particle size cut size. (The cut size is defined as the particle size corresponding to the 50% recovery point on the partition curve, and is considered to be separation size for a given test.) As stated previously, variations in the characteristics of the feed (such as solids content) do not significantly impact the cut size since the teeter water velocity remains constant throughout the unit. As a result, the particle size cut size is controlled

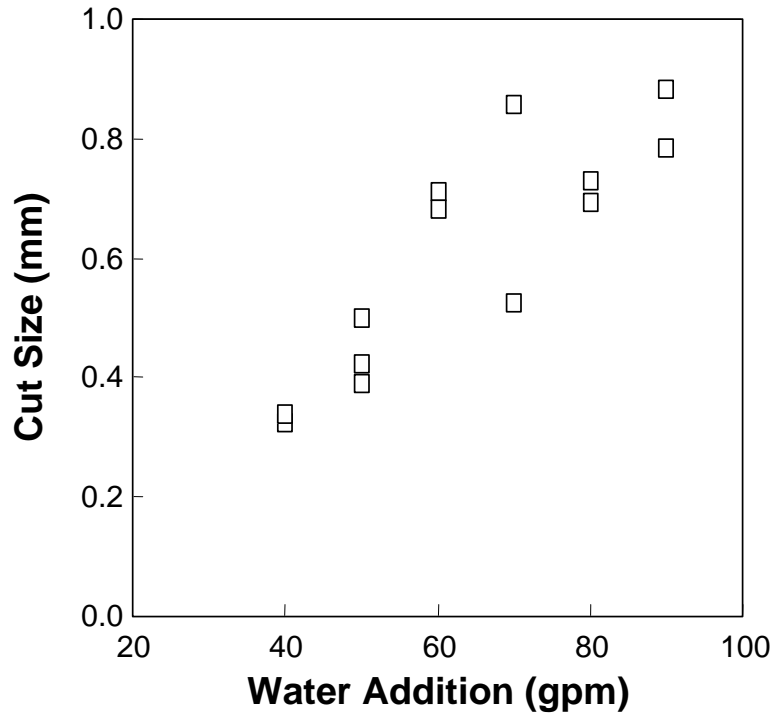


Figure 4.3. Particle cut size versus fluidization water rate.

predominantly by the teeter water flow rate. In fact, the data in Figure 4.3 show that an approximately linear relationship exists between flow rate and particle cut size. As a result, on-line adjustment of size of the overflow and underflow products can be achieved through simple water flow control for the CrossFlow classifier.

4.1.2 Full-Scale Prototype Test Results

In light of the promising results obtained using the pilot-scale CrossFlow unit, a full-scale classifier at an industrial phosphate beneficiation plant was retrofit using the CrossFlow feeding system. The results obtained from this unit were then compared to those obtained from the conventional full-scale classifiers operating in parallel to the CrossFlow system at the plant. Due

to fluctuations in the plant feed tonnage, the test results are reported as an average of seven sets of experiments conducted over a range of dry solids feed rates from 1270 to 1800 tph (circuit). In each test, representative samples of feed, oversize and undersize solids were collected and subjected to sieve analysis. The resulting size data were used to construct partition curves for both the conventional and CrossFlow units. The data points were then fit using an empirical partition function given by:

$$P = (\exp\{\alpha(d/d_{50})\} - 1) / (\exp\{\alpha(d/d_{50}) - \exp\{\alpha\} - 2)$$
 [2]

in which P is the partition factor, d the particle size, d_{50} the particle size cutpoint (defined at P=50%), and α is a parameter that reflects the sharpness of the size separation (defined as the slope at P=50%). Note that a larger value of α indicates a sharper (more efficient) particle size separation.

The results of the side-by-side comparison of the conventional and CrossFlow classifiers are provided in Table 4.2. As expected from the laboratory and pilot-scale data, the full-scale test results show that the CrossFlow reduced the particle cut size from 729 to 362 microns while maintaining the same feed throughput. At the same time, the CrossFlow substantially improved the efficiency of sizing (α increased from 3.4 to 8.1). In fact, the amount of misplaced coarse

Table 4.2. Comparison of full-scale conventional and CrossFlow classifiers.

Test Variable	Conventional	CrossFlow
Particle Cut Size	29 μm	362 μm
Alpha Value	3.4	8.1
Misplaced +35 Mesh	9.0%	1.7%

(+35 mesh) solids in the fine product overflow was reduced by more than five-fold (from 9.0% to 1.7%). These impressive results illustrate the superior performance of the CrossFlow separator for industrial classification applications.

4.2 Phosphate Upgrading Using the HydroFloat Concentrator

4.2.1 Pilot-Scale Test Results

Several series of in-plant tests were conducted to assess the capabilities of the HydroFloat separator for upgrading coarse phosphate matrix. The test program was carried out using a pilot-scale HydroFloat unit. Feed for the test unit was taken from an existing slurry distributor that fed an identical pair of 8-foot diameter rougher-scavenger flotation cells. Prior to flotation, the feed was reagentized with a fatty-acid/fuel oil blend and conditioned in stirred-tank conditioners at 72% solids. Soda ash was used to control pH. During testing, fluidization (teeter) water was introduced into the bottom of the separator to create a fluidized bed of phosphate particles. Air and frother were passed through a bubble generator and injected through the water distribution network. The air bubbles, which selectively attached to hydrophobic particles, created low-density bubble-particle aggregates that were recovered as overflow product. The hydrophilic particles (sand) were rejected as a waste stream through a discharge valve at the bottom of the unit. Twelve test runs were completed using the test conditions summarized in Table 4.3.

The results from the in-plant testing of the pilot-scale HydroFloat separator are summarized in Table 4.4. The BPL recoveries ranged from a low of 90.1% to a high of 98.2% over the range of test conditions evaluated. Under optimal conditions (i.e., highest separation efficiency), the HydroFloat provided a product grade of 11.4% insol and 64.6% BPL. These single-stage results compare very favorably to the existing two-stage rougher-scavenger flotation

Table 4.3. Test conditions for the pilot-scale HydroFloat concentrator.

Test Run	Teeter Water Rate (gpm)	Aeration Rate (scfm/ft ²)	Reagent (lb/ton)
1	13.4	1.27	0.80
2	13.4	1.27	0.80
4	10.2	1.27	0.80
5	11.5	1.06	0.90
6	11.5	1.06	1.00
7	11.5	1.06	1.00
8	11.5	1.06	1.00
9	11.5	1.06	1.00
10	11.5	0.85	1.00
11	11.5	0.85	1.00
12	11.5	0.64	1.00

Note: Feed Rate = 1.3 tph/ft²; Feed Solids = 50%

Table 4.4. Test results for the pilot-scale HydroFloat concentrator.

No.	Conc. Grade (%)		Distribution (%)		Effic. (%)
	BPL	Insol	BPL	Insol	
1	36.9	50.2	98.2	50.3	48.5
2	46.3	37.6	98.2	63.3	61.5
4	60.5	17.8	94.0	77.0	71.0
5	53.0	26.6	93.0	84.7	77.7
6	64.6	11.4	90.1	88.1	78.2
7	59.8	18.7	96.6	74.9	71.4
8	50.8	30.1	97.8	54.1	51.9
9	60.4	17.9	95.8	77.4	73.1
10	55.8	24.6	94.6	67.8	62.4
11	56.1	23.3	97.8	66.5	64.3
12	63.4	13.9	93.5	81.6	75.1

Note: Average Feed: BPL = 35.8%, Insols = 51.8%

circuit currently in operation at the plant. The two-stage circuit historically provides a froth product containing about 20% insol and 60% BPL. Therefore, these results indicate that the HydroFloat can achieve a comparable separation after only a single-stage of processing.

4.2.2 *Full-Scale Prototype Test Results*

Based on these very promising results of the pilot-scale tests, several sets of follow-up tests were undertaken at the industrial plant site using a full-scale (8 ft diameter) column cell that had been retrofit with the HydroFloat technology. For comparison, samples were collected from the plant conventional rougher flotation cell so that a fair performance comparison could be made.

Figures 4.4 and 4.5 show the recovery-grade curves obtained from the pilot- and full-scale HydroFloat test programs, as well as data from the conventional rougher flotation bank at the plant site. Several important observations can be made. First, the data points appear to fall along essentially the same recovery-grade curves, suggesting that the selectivity of the separation is largely dominated by the surface properties (wettability) of the particles. Second, the results suggest that the performance of the full-scale HydroFloat unit can be projected based on test data obtained from the pilot-scale test unit. This finding is particularly important for scale-up reasons. Finally, the side-by-side comparison clearly demonstrates that the HydroFloat technology is capable of providing a significantly higher recovery of valuable product than can be obtained using a comparable volume of single-stage conventional flotation cells. For the current test program, the best full-scale HydroFloat test run provided a BPL recovery of 95.9% with a product having BPL and insol contents of 68% and 7.7%, respectively. In comparison, the conventional froth flotation column was able to achieve a BPL recovery of just 82.8%. Thus, additional stages of conventional scavenger flotation are required at the plant in order to improve the recovery to an acceptable level.

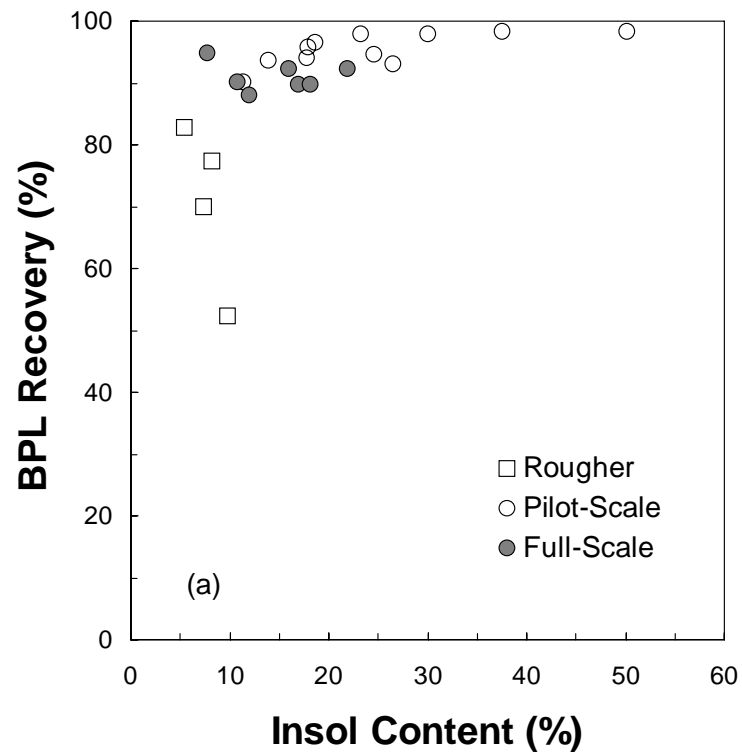


Figure 4.4. Recovery versus insol content for different test runs.

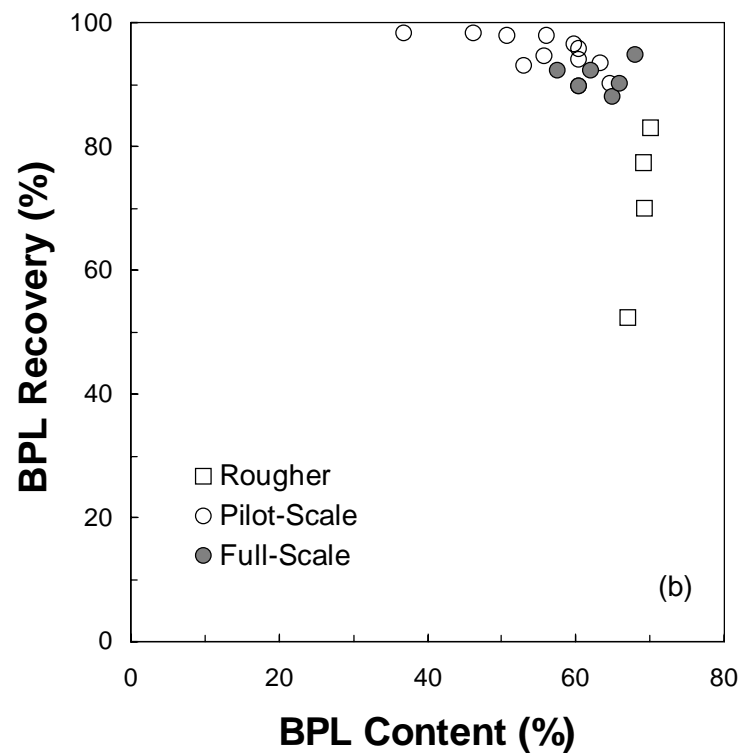


Figure 4.5. Recovery versus BPL content for different test runs.

Table 4.5. Comparison of power and reagent demand.

	HydroFloat Circuit	Existing Circuit	Net Change
<i>Power Usage:</i>			
Water (HP)	46.6	92.4	---
Air (HP)	38.0	0.0	---
Net Total (HP)	84.6	92.0	-8.4%
<i>Reagents:</i>			
Frother (lb/t)	0.05	0.08	-40.0%
FA/FO (lb/t)	0.80	1.00	-20.0%
FO (lb/t)	0.00	0.60	-100%

The results obtained from the industrial site indicate that the HydroFloat also offers significant cost advantages by consuming less electrical power, process water, and chemical reagents than conventional processes. For example, Table 4.5 compares the expected power and reagent usage for the HydroFloat and conventional circuits for the test site described above. In this case, the installation of the HydroFloat technology would be expected to reduce the net horsepower requirement by 8.4%. In addition, the HydroFloat would require 40% less frother, 20% less fatty acid/fuel oil mixture (rougher), and 100% less fuel oil (scavenger).

4.3 Fine Coal Cleaning Using the CrossFlow Concentrator

4.3.1 Pilot-Scale Test Results

This task involved the testing of a pilot-scale CrossFlow separator to determine whether the installation of one or more full-scale units could be justified at a new plant in Kentucky. Since the plant did not yet exist, the pilot-scale testing was performed at a nearby facility treating a similar coal feed. The goal of this effort was to determine the anticipated product yield and grade, combustible recovery, and feed capacity of the test unit in order to predict the expected performance of a full-scale prototype.

The 9 x 16 inch CrossFlow separator was transported from the manufacturer's site to the coal preparation plant and was installed with assistance provided by the plant operators and mechanics. Feed was supplied to the unit through a 2-inch feed line connected to the existing coal spiral slurry feed distributor. A slurry splitter fabricated from PVC pipe with a tee and valves was used to regulate the feed to the unit, with the remaining slurry reporting to the spiral circuit. Underflow and overflow material was discharged to sizing screens in the plant, located on a level below the unit. Plant compressed air and electrical power were connected to the separator for the automated control system. The separator was automatically controlled through the use of a simple PID control loop, which includes a pressure sensor mounted on the side of the separator to measure the relative pressure (level), a single-loop PID controller, and a pneumatic pinch valve to control the underflow discharge to maintain a constant bed pressure (level). Clarified water was connected to the separator to create the fluidized teeter bed of solids.

Preliminary shakedown testing of the pilot-scale unit was conducted after completing the installation to resolve any unexpected operational problems that could arise. Once the circuit was operational, two series of detailed tests were then conducted. The first series of tests were performed to investigate the effects of the key design variables on separator performance and to simultaneously define the overall grade and recovery curve, while the second series of tests were conducted to investigate the effects of key operating parameters. The most important operating variables were found to be teeter bed pressure and fluidization water rate. The coal/rock interface, or teeter bed surface, was adjusted to different levels (i.e. different bed pressure) for each steady-state test. Fluidization water was adjusted to fine tune the separation. Other variables examined included solids mass feed rate and volumetric slurry feed rate. For each test, samples

were taken from the feed, overflow, and underflow streams after conditions were stabilized. The samples were analyzed for ash and sulfur contents on a size-by-size basis.

As shown in Table 4.6, nine test runs were completed during the on-site test work. The experimental results are shown graphically in Figures 4.6 and 4.7. The results are plotted as with the passing 100 mesh material mathematically removed from the data. This approach is acceptable as it is expected that the clean coal product will be deslimed in the plant at 100 mesh (0.150 mm) using sieves and the fine material upgraded by flotation.

As shown in Figure 4.6, the pilot-scale test work was clearly able to define the expected grade and recovery curve for this particular coal. Specifically, the CrossFlow separator was capable of producing a clean coal product having 6-11% ash at a combustible recovery of greater than 97% (when deslimed at 100 mesh). At the maximum separation efficiency, the combustible recovery for this application approached 98%. The data presented in Figure 4.7 indicates that the sulfur content of the corresponding product was 1.50%.

Table 4.6. Test conditions used for the on-site pilot-scale testing of the CrossFlow unit.

Test Number	Feed			Level inches	Water gpm
	% Solids	tph	gpm		
1	32.55	1.83	20	14.5	8
2	34.44	1.95	20	20.0	8
3	35.24	2.00	20	10.0	8
4	35.71	1.73	17	10.0	9.5
5	32.90	2.22	24	14.5	9.5
6	32.71	1.84	20	20.0	9.5
7	35.21	2.00	20	20.0	6.5
8	34.10	1.93	20	14.5	6.5
9	33.55	1.89	20	10.0	6.5

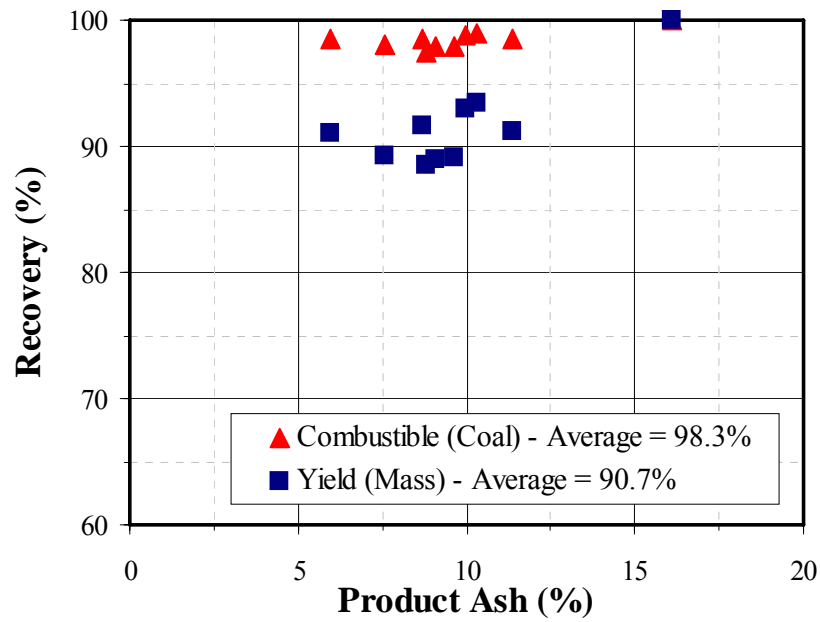


Figure 4.6. Recovery versus product ash for the plus 100 mesh coal.

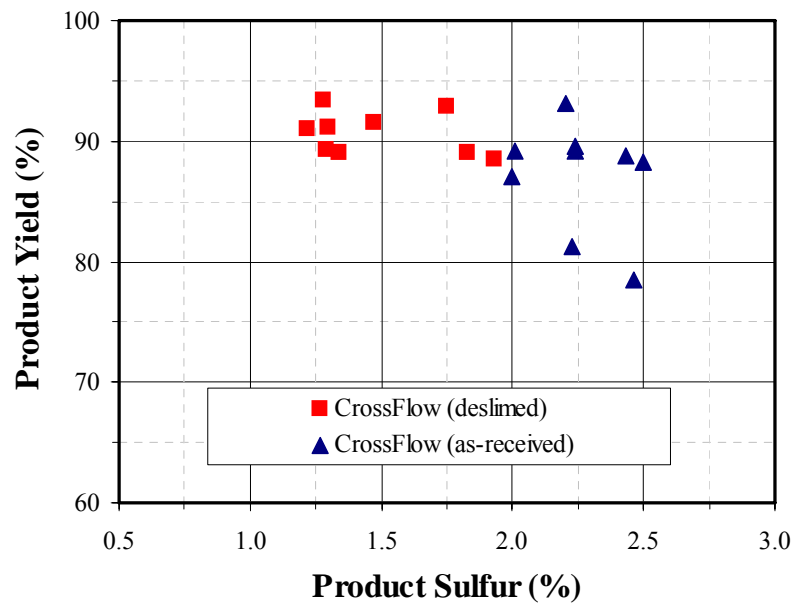


Figure 4.7. Mass yield versus product sulfur for the plus 100 mesh coal.

4.3.2 Full-Scale Prototype Test Results

Following the successful completion of the pilot-scale testing, the participating coal company elected to install a full-scale prototype CrossFlow separator for cleaning the intermediate size fraction (2.0 x 0.25 mm) of raw coal for a new 650 tph green-field preparation plant in Kentucky. The expected material balance for the prototype circuit is shown in Figure 4.8. The feed to the prototype unit was expected to contain approximately 175 tph of feed coal at about 50% solids. The pilot-scale test work demonstrated the ability of the CrossFlow separator to handle this entire flow using a single-stage 9 x 9 ft separator (offering 81 ft² of cross-sectional

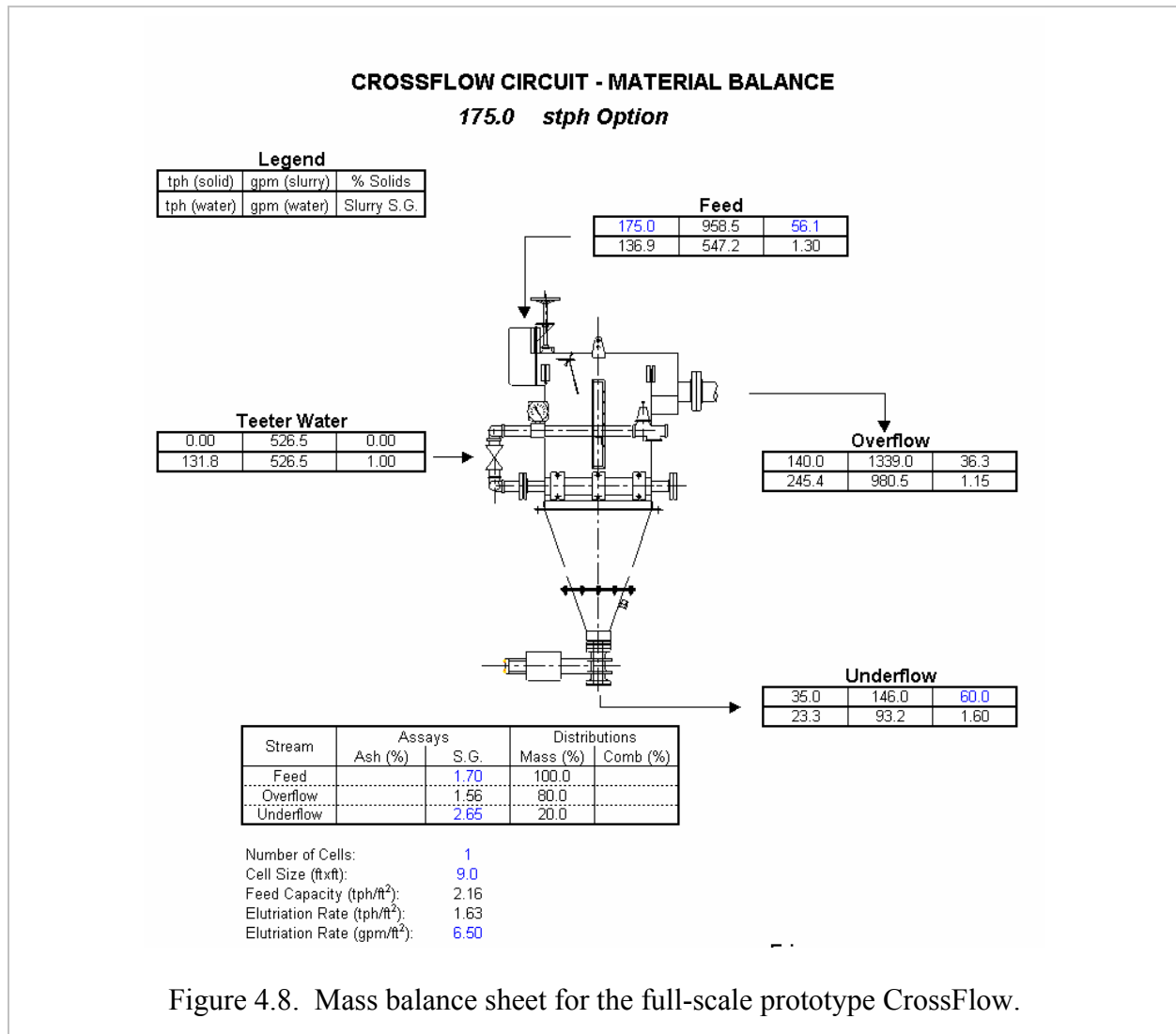


Figure 4.8. Mass balance sheet for the full-scale prototype CrossFlow.

area at a normalized feed rate of 2.1 tph/ft²). The remaining tonnage in other size fractions fed to the plant were treated with heavy medium cyclones (2 inch x 2 mm) and conventional froth flotation cells (0.25 mm x 0).

The CrossFlow separator was manufactured by Eriez Manufacturing and installed in the new preparation plant by the participating coal company. A photograph of the installed prototype separator is shown in Figure 4.9. The clean coal product (overflow) from the unit is deslimed at 65 mesh (0.25 mm) using a sieve screen and horizontal vibrating screen, combined with the flotation product, and dewatered in a screen-bowl centrifuge circuit. The reject (underflow) is dewatered on horizontal vibrating dewatering screens and directed to the plant rejects conveyor.

Shakedown testing for the prototype unit included a visual inspection of all the components after the installation, operating the unit on water to check the control devices, and



Figure 4.9. Photograph of the installed full-scale CrossFlow separator.

tuning the control system after adding raw coal feed. The teeter-bed density, which controls the separating density, is automatically maintained by a PID controller with an input from a differential pressure (DP) cell transmitter located in the lower section of the separating zone. The output from the controller manipulates a proportional valve on the underflow discharge pipe. The elutriation water is controlled manually using a simple valve arrangement. During start-up and commissioning, the unit produced a clean coal product with an ash content of approximately 10% at a combustible recovery of better than 90%.

After shakedown testing, three sequential series of evaluations were conducted during the 11 month period after start-up. In each series of tests, the feed, product, and reject streams were sampled during a normal operating shift. A sample of the feed was also taken and subjected to float-sink analysis so that the theoretical best level of performance could also be established for this particular feed coal. The results from the first series of “preliminary tests” are presented in Figure 4.10. The performance data show that the combustible recovery regularly exceeded 90% with product ash values ranging between 10% and 12%. While these results were very good, the second series of “detailed tests” were conducted with the objective of further improving recovery while maintaining product grade. The evaluations were conducted while running the unit at the highest available teeter-bed pressure (bed level) while varying the elutriation water rate. The maximum level was limited by the calibration of the existing DP cell transmitter. As shown in Figure 4.11, the detailed tests resulted in an incremental improvement in separation performance. By operating with the teeter-bed at the highest level, the average combustible recovery and yield improved by nearly 2%, while the product ash remained in the 10% to 12% range. This series of testing suggested that further performance improvements could be realized by increasing the teeter-bed level.

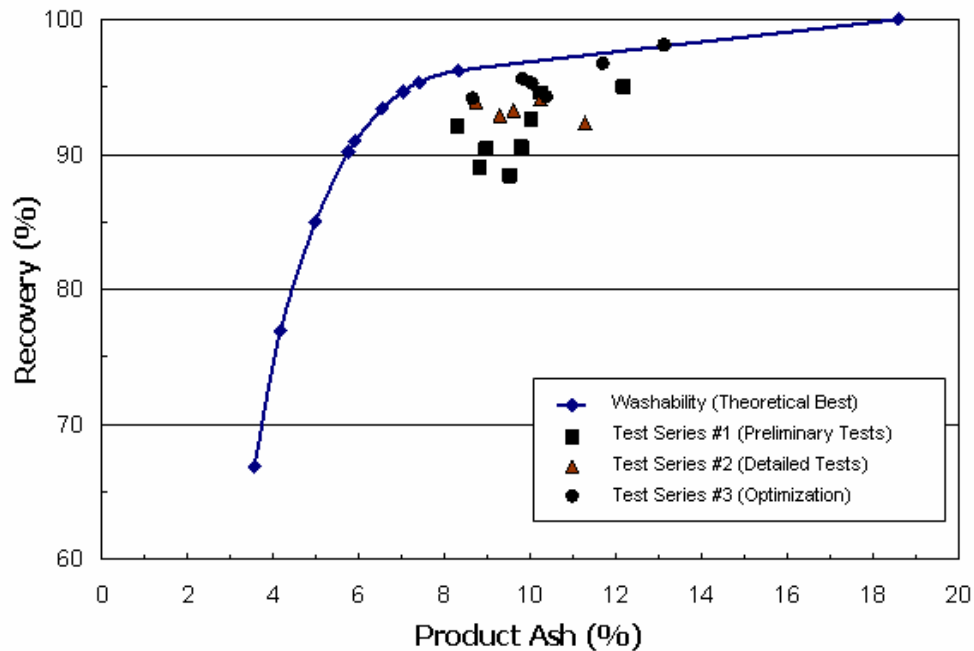


Figure 4.10. Experimental results from three series of full-scale CrossFlow tests.

The third series of testing was performed after recalibration of the DP cell transmitter so that the unit could be operated at higher teeter-bed levels than those that were used during the first two series of tests. The results of these “optimization tests” are also presented in Figure 4.10. By operating the unit at a higher teeter-bed level (higher densities), the recovery was improved by an additional 2 percentage points. In fact, this mode of operation provided a separation performance that was in very good agreement with that projected based on the pilot-scale experiments. The systematic approach of optimizing the CrossFlow separator resulted in an average increase in product mass yield of over 4 percentage points, which equates to about 5.9 tph of additional clean coal. Using the current typical market price for thermal coal of \$50.00 per ton and scheduled production of 4,000 hours per year, this improvement increased the annual revenue from this circuit by about \$1.2 million.

After optimizing the performance of the unit, a long-duration test run was performed under the optimum conditions identified from the earlier test runs. In this case, sample increments were collected at regular intervals during an 8-hour shift for the feed, product, and reject streams. The resultant samples were combined and subjected to laboratory analyses. The results obtained from this test run are shown in Table 4.7. The separator produced a clean coal ash of about 9.5% at a mass yield of 84.7% and combustible recovery of 93.5%. At the same ash content, the float-sink data for this particular sample was found to produce a theoretical clean coal yield of 87.1%. As such, the CrossFlow separator provided an exceptionally good organic efficiency of 97.3% for this particular application.

Table 4.7. Results of a long duration (8 hr) CrossFlow test under optimum conditions.

Feed Ash (%)	Product Ash (%)	Reject Ash (%)	Mass Yield (%)	Combustible Recovery (%)
17.95	9.51	64.80	84.74	93.46

5.0 CONCLUSIONS

Hydraulic separators are used in the mineral and coal processing industries to classify and/or upgrade particles according to size, shape or density. Unfortunately, current designs are typically inefficient, resulting in substantial losses of valuable resources. In response to this problem, a new generation of hydraulic separators, known as the CrossFlow Classifier and HydroFloat Separator, has been developed based on fundamental processing engineering knowledge. In order to promote industry implementation, a field study was undertaken (i) to further develop these new technologies through systematic pilot-scale testing of key design and operating variables and (ii) to demonstrate the improved performance at industrial sites using full-scale prototypes.

The pilot-scale data collected to date indicate that these high-efficiency separators can substantially improve the performance of classification and concentration circuits. In light of these promising results, full-scale prototypes of the CrossFlow and HydroFloat technologies have been purchased by mining companies for further testing and evaluation. Two of the prototype units were installed by a major U.S. phosphate producer and one by a major coal producer. The field data obtained from the full-scale evaluations demonstrated that these technologies offer significant improvements in terms of metallurgical performance (e.g., higher recovery and throughput capacity) and lower operating cost (e.g., lower consumption of electrical power, process water, and chemical reagents) than conventional processes.

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